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The Advanced Materials Program Plan . . .

the Continuation of a Presidential Commitment

Executive Office of the President
National Critical Materials Council

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NATIONAL CRITICAL MATERIALS COUNCIL

Donald Paul Hodel, Chairman

Thomas G. Moore, Member

David S. Brown, Executive Director

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EXECUTIVE SUMMARY

This national Federal program plan for advanced materials research and development (R&D), known as the Advanced Materials Program Plan, is in fulfillment of Sec. 202 (b)(2) and Sec. 205 (1)(A) of the National Critical Materials Act of 1984, Public Law 98-373.

The plan presents three important aspects of advanced materials R&D. The first is the technical constraints which challenge advanced materials researchers. Secondly, the plan presents the research activities of the major Federal agencies with materials programs and the mechanisms to coordinate their activities. Finally, the Federal policies that affect materials R&D are assembled into a policy framework.

The U.S. Government has budgeted over $1 billion in materials research for fiscal year 1989. The research concentrates on long-term, high-risk, high-potential payoff projects with the best chance for wide generic applications to materials problems and increased productivity. The research is concentrated in six executive departments and agencies. The departments with the largest materials budgets are the Department of Energy with $480 million and the Department of Defense with $181 million. Other departments with substantial materials budgets are the National Aeronautics and Space Administration, $157 million; the National Science Foundation, $137 million; the National Institute of Standards and Technology, $24 million; and the Bureau of Mines, $24 million.

Research is being conducted, and there is a continuing need for work to better understand structure-property relationships. Improved physical property data bases, nondestructive evaluation methods, and deterioration-in-use assessment methods are also needed in order that new materials can be used to their full potential. Improvements in joining technologies are essential in manufacturing reliable advanced materials systems.

Metals and alloys researchers have been concentrating on new processing techniques such as rapidly solidified alloys, as well as new alloys such as aluminum-lithium. In structural ceramics, control of critical flaws is the key to improving reliability and avoiding catastrophic failure. Engineering polymer research has focused on methods to control surface finishes and improve coatings. The issue of recyclability is one which is especially important in regard to new polymer materials systems. In composites, understanding the forces operating between the matrix and the reinforcing material is important to producing uniform and predictable products. In the electronic, magnetic, and optical materials areas there are many types of research taking place. Perhaps the most important of these is superconductivity research.

There are nine policy areas that have been identified as crucial to the development of advanced materials. These policy areas are as follows:

1. Coordination and communication within Government.

2. Coordination and communication among Government, industry, and academia, including but not limited to technology transfer.

3. Antitrust constraints (perceived and actual) on joint R&D ventures.

4. Intellectual property rights.

5. Product liability and tort law.

6. Education.

7. The Government's role in R&D funding, including tax incentives.

8. General regulatory policies.

9. International issues regarding R&D, including cooperation and export control policy.

The linking of these issues to the Government's actions provides an important component of the Program Plan. This plan presents the current status of advanced materials R&D. Followup is needed to ensure that the actions initiated by the current Administration bring about their intended results. Efforts are needed to continue to improve coordination of advanced materials R&D among the involved agencies, as well as the National Critical Materials Council, the Office of Management and Budget, and the Office of Science and Technology Policy. The issues identified here must continue to be reviewed so that existing mechanisms can be improved and new actions taken where needed.

PART I

INTRODUCTION

Advanced materials are difficult to define apart from the systems in which they are used. Advanced materials are important for direct security reasons when used in military applications, and a subset of these can go on to become economically important. There are some materials that have more immediate nonmilitary applications in mass markets, such as sporting goods and medical and dental applications.

WHAT ARE ADVANCED MATERIALS?

Advanced materials are difficult to define in one simple sentence or phrase. One of the attributes that typifies advanced materials is that it is hard to separate them from their end-use systems. This in turn creates problems for the classification of these material systems, where material type, form, and function can overlap.

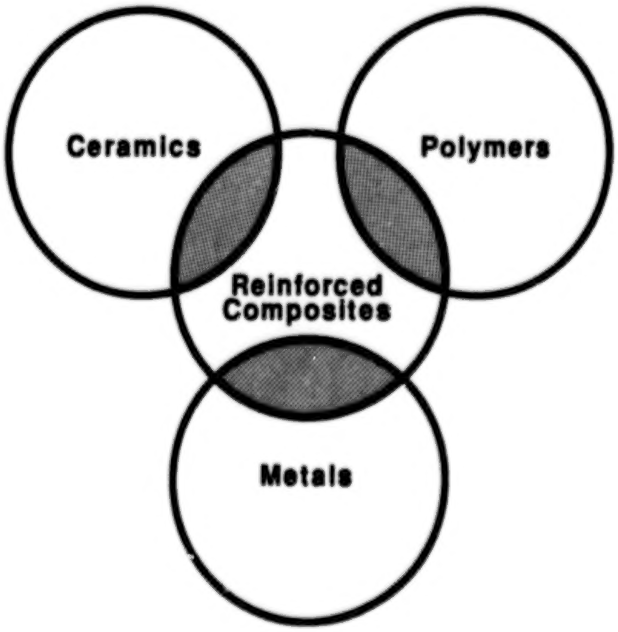
While there are several competing proposed advanced materials classifications, they all make use of material type, functional form, composition, and specified end-usage to define these new materials. The three basic structural material types are metals, ceramics, and polymers. As indicated in Figure 1-1, composites consist of combinations of these three material types.

Functional categories can include, for example, structural and absorptive metals, electronic and structural ceramics, and structural and electronic engineering polymers. Polymeric composites are associated with mechanical or structural functions. Metal matrix and ceramic matrix composites are associated with thermal functions.

Generally, advanced materials exhibit greater strength; higher strength/density ratios; greater hardness; and/or one or more superior thermal, electrical, optical, or chemical properties when compared with traditional materials currently used in large-volume, assembly line production. These attributes either allow for very significant improvements in product or device performance or, perhaps more significantly, allow for new technologies that were not achievable using the conventional materials.

The link between an advanced material and the final product in which it is used is important because the material is manufactured in consideration of the design and function of the end-use. The fundamental difference between advanced materials and conventional materials is that in the past designers worked within the constraints of the selected material—often designing around the constraints. Today the designer can look at a material as a means to overcoming constraints that might exist elsewhere in the end-use system. These "performance" characteristics of the new materials often require manufacturing technologies and process controls which are considerably more sophisticated than conventional materials processing techniques.

Figure 1-1. The Family of Structural Materials



Source: OTA July 1988 - Modified

The world of advanced materials, therefore, is inhabited not only by the materials and end-use systems themselves, but by the new manufacturing technologies with which these materials become possible. The pull of technology is circular, with new materials allowing for new technical applications which in turn demand more sophisticated process technologies. An advanced material is then by nature a dynamic concept—implying not so much a particular chemical makeup, but rather a process by which the material is an active component in the solution to an engineer's or designer's challenge. The chemical makeup is useful, however, in the formal taxonomy of advanced materials, as distinct from a general conceptual definition of them.

The jury is still out on how exactly to categorize advanced materials as distinct from conventional materials. There is a general agreement among experts that advanced materials are key factors to enabling new technologies and innovations. This aspect of the new materials, perhaps more than any other, gives rise to the attention they have been given by policymakers in both the public and private arenas.

WHY ARE ADVANCED MATERIALS IMPORTANT?

There are several important industries which will drive technological changes, national security considerations, and economic advances well into the next century. Of these industries, three of the most important are information/communications systems (computers), biotechnology, and advanced materials systems. Of the three, advanced materials are the most far-reaching, and are important to advances in the other two fields.

Materials considerations cross-cut all industries. There is not an "advanced materials industry." However, there are some industries (aerospace, for example) where the materials considerations are so important as to make them a dominant consideration in the product design.

Materials suppliers to these industries could be considered as being part of the "advanced materials industry." However, the intimate relationship between materials design and end-use application tends to make the materials producer an industry-specific materials supplier, unlike steel or aluminum producers who supply materials used in many applications. As a result, the product-specific nature of advanced materials is a liability in terms of designing a unified policy and, as mentioned above, to even defining the industry, since it tends to be broken into many component industries.

The military is often the first and sometimes the only market for many of the most technically advanced materials and, therefore, can be the "driving" force for many of the new materials. The civilian aerospace program can also create the initial demands for new materials and applications. The above is true because in military and aerospace applications performance is the most important criterion and material cost is secondary.

Materials that eventually become cost-effective for nonmilitary applications have the potential to become high-volume materials utilized throughout the economy. Therefore, advanced materials are important for direct security reasons when used in military applications, and a subset of these can go on to become economically important. There are, of course, some materials that have more immediate nonmilitary applications in mass markets, such as sporting goods and medical and dental applications.

The economic stakes in terms of future gross national product (GNP) are high. The U.S. Bureau of Mines has estimated that by the early 21st century the U.S. engineering polymers market will be about $7 billion; advanced polymer composites, $12 billion; advanced ceramics (including fiber optics), $17 billion; and advanced specialty metals, alloys, and composites, $19 billion—for a total market of about $55 billion per year. The Japanese market will be about $34 billion per year for the same materials. The European market is estimated to bring the total world market to about $100 billion per year. Yet dollar value of the materials alone does not reflect the full impact of these materials, since it is the technology which they enable that ultimately plays the important national security, economic, and social role.

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Our overseas competitors, principally the Japanese, have embarked on aggressive national campaigns to secure certain percentages of the world market in selected materials and in their end-use systems. Future competition in the world automobile market, for example, can be seen largely in terms of advanced materials systems. Those cars which are designed to economically incorporate the latest in materials technology—whether it is polymer composite auto bodies or ceramic turbochargers—will have an advantage on the world market. The consumer, for the most part, does not care about the materials directly, but more about engine performance, gas mileage, maintenance and repair, and the cost of purchasing and maintaining the automobile. Ultimately, the material systems determine, to a large degree, the cost and performance of the final product.

The United States has long been a leader in science and technology. For example, our university system remains the envy of the world. The challenge before the Nation is to translate the ability to do basic research into products which embody that comparative scientific advantage that can be sold competitively on the world market.

This challenge must be met by government and industry alike. The Federal Government, for its part, is a major player by nature of the role of advanced materials in military applications and government support for basic science and generic research at universities and the national labs. Industry must balance short-term profits with research and development (R&D) requirements in order to stay competitive in world markets by developing and implementing innovative, advanced products.

The policy debate centers on the ground where the public and private sector meet: technology transfer from public to private institutions, the degree of government involvement in types of research and development, the barriers that may exist to commercialization of these new materials, and the economic incentives to innovation and product development. U.S. policymakers must take careful steps to ensure that government actions are appropriate, address legitimate social costs, and foster the efficient operation of the market in its allocation of resources.

WHAT IS THE GOAL OF THIS PROGRAM PLAN?

To chart a path for the future, we must first take stock of the present. The goal of this Program Plan is to look at where the country stands today in advanced materials. There are three major aspects of this:

1. The technical constraints which challenge materials researchers.
2. The research activities of the Federal Government.
3. The Federal policies that affect materials research, development, and commercialization.

Understanding the technical constraints sheds light on the current limitations of advanced materials systems. The research activities of the Federal Government show what government experts believe to be the important materials aspects of their agencies' missions. Finally, the Federal policy framework will provide for discussion on how to achieve an environment that is conducive to advanced materials R&D. These three components provide the basis for the Advanced Materials Program Plan.

WHAT IS THE METHODOLOGY OF THIS PROGRAM PLAN?

The technical constraints were assembled by reviews of the literature and discussion with experts in the various related fields. The agency research activities were assembled from programs presented at an advanced materials workshop. The agencies with the largest materials budgets were invited to present their current technical work. Agency personnel supplemented this with information provided at meetings of the interagency groups—the Committee on Materials and the Interagency Materials Group—whose purpose it is to share technical information.

The methodology to assemble the important policies is more complex. The first of two workshops was given so the private sector

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participants could present their ideas on the dominant issues related to advanced materials. It became clear that most of these issues were generic to all R&D. The next step was to examine recent legislation and executive initiatives which addressed these issues. These were assembled into an advanced materials policy framework.

HOW IS THIS PROGRAM PLAN STRUCTURED?

Part I is this introduction. Part II of the Program Plan introduces the reader to advanced materials systems. The history of materials is discussed, and they are placed in the current economic context. Part III is a more technical discussion of the classification of and uses for advanced materials. The technical constraints on advanced materials development are presented at the end of Part III. Part IV presents the mineral- and material-related programs and technical agendas of Japan, Europe, and the United States. The programs of U.S. Federal agencies with the largest materials budgets are presented in Part IV.

Part V focuses on issues that have been identified in at least one of the following four ways:

1. Recent studies which analyze the advanced materials industries and possible barriers to new materials commercialization.

2. Roundtables held specifically for input into the Program Plan.

3. Communications between National Critical Materials Council members and staff and individuals in the private sector materials community.

4. Council discussions with personnel from Federal agencies with advanced materials R&D programs, including Council staff participation in the activities of the Committee on Materials.

Part V links these issues to recent legislative and administrative actions and develops the policy component of the Program Plan. Part VI summarizes the components of the Program Plan and draws conclusions. An appendix provides additional information for the interested reader.

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PART II

OVERVIEW: THE PAST, PRESENT, AND FUTURE ROLE OF MATERIALS IN SOCIETY

Advancement of civilization has been inextricably linked with availability of materials, from which useful articles can be made, and with the availability of energy for processing those materials. The advanced materials of today differ from materials of the past in that manufacturers now develop the materials to satisfy design and performance requirements rather than limiting the design and performance to the materials.

OVERVIEW: THE PAST, PRESENT, AND FUTURE ROLE OF MATERIALS IN SOCIETY

Throughout human existence, advancement of civilization has been inextricably linked with availability of materials, from which useful articles can be made, and with the availability of energy for processing those materials. The Stone Age, the Bronze Age, and the Iron Age were named for the most important materials used at the time, and each represented a major advance in the ability to use materials for practical purposes. New levels of knowledge and skill were attained in order to make the new materials and to apply them to new uses.

Much of the course of human history, especially conflict, has been determined by the uneven distribution of these mineral and energy resources. Early exploration, trade, and conquests were in large part spurred by the need for minerals to sustain new materials industries.

International competition based on materials development is not a new phenomenon. It is reasonable to ask why the "advanced materials" of the 1980's are receiving so much attention. The following summary of materials development placed in the historical context of science and industry, along with a glimpse at the near future, is an attempt to answer that question.

PRE-INDUSTRIAL REVOLUTION

Just prior to the industrial revolution, only seven metals—copper, tin, lead, iron, gold, silver, and mercury—were in common use; all were the same metals as those used in ancient times. Coal, wood, and charcoal were the available energy sources; sulfur and nitrate, for the making of gunpowder, constituted the chemical industry; stone, clay, wood, gypsum, and lime, supplemented by the newly developed portland cement, were the available materials of construction. The industrial revolution began in the Iron Age, and only with the development of efficient methods for production of large tonnages of high-quality steel was modern industrialized society possible.

THE INDUSTRIAL REVOLUTION (1750 TO 1850)

As indicated in Figure 2-1, the industrial revolution began to develop in the late 18th century with the invention of the steam engine in 1769 and was given added impetus by the development of the first steelmaking process (puddling) in 1784. Steam power was rapidly applied to manufacturing, to water transportation (the steamship, 1807), and to land transportation (railroad, 1825).

The late 18th century and early 19th century also witnessed the beginning of modern science with development of Lavoisier's law of conservation of mass (1772), Dalton's atomic theory (1807), and Avogadro's law (1811). The first synthesis of an organic compound was that of urea (1828).

The invention of the steam engine, the first source of mechanical power using chemical energy, and the development of an understanding of the structure of matter and the laws of thermodynamics combined to set the stage for modern industrial society in the latter half of the 19th century.

THE BIRTH OF THE INDUSTRIAL SOCIETY (1850 TO 1900)

As shown in Figure 2-2, the Bessemer process, by which air is blasted through molten metal to remove carbon and other elements, was developed in 1856 and by 1865 was producing large quantities of high-quality steel which, by virtue of its much greater toughness and tensile

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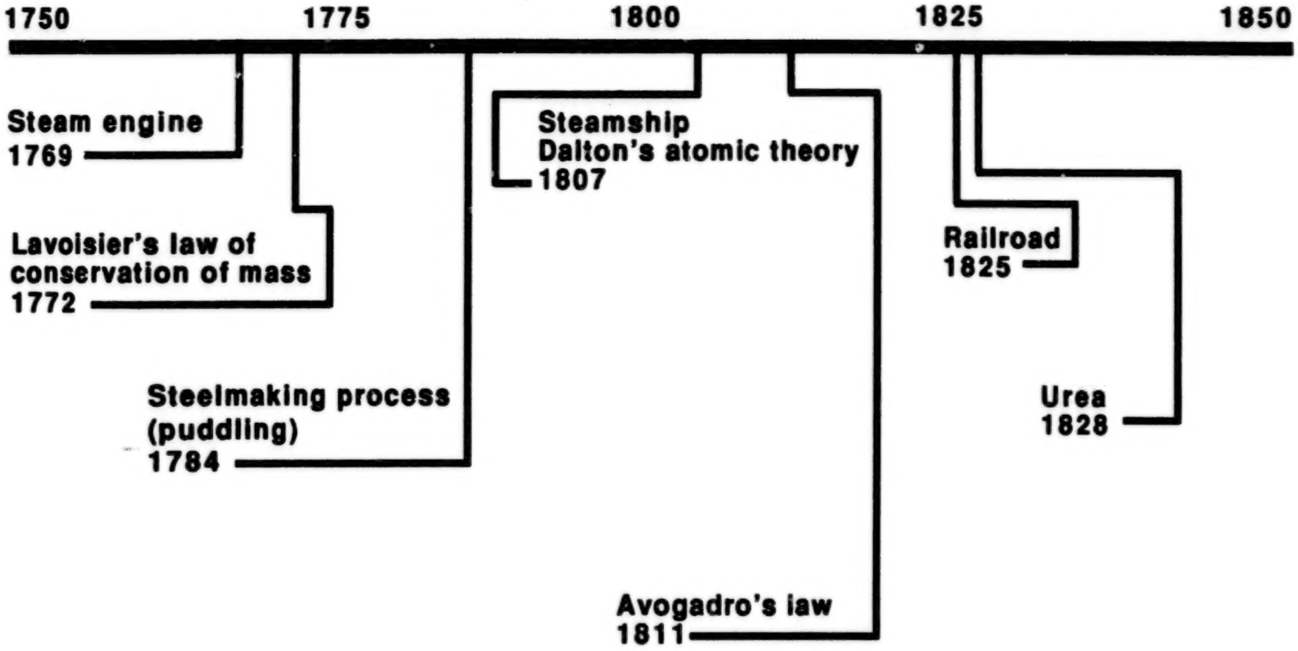
Figure 2-1. The Industrial Revolution (1750 to 1950)



Source: Light and Shadow: The Two Aspects of the New Materials Business, Industrial Bank of Japan, August 1986.

strength, replaced wood and wrought iron as the industrial material of choice. Steel was thus the first mass-produced commodity material. The Bessemer process later gave way to the blast furnace method, which, though slower, produced a better quality steel, and subsequently to today's basic oxygen furnace and electric arc steelmaking and continuous-casting methods. Improvement of the properties of steel required use of increasing numbers of other metals for deoxidation, sulfur removal, grain refining, and improvement of hardness, strength, corrosion resistance, and magnetic and electrical properties. Elements such as manganese, chromium, silicon, molybdenum, nickel, tungsten, vanadium, titanium, columbium (niobium), cobalt, and zirconium were developed for uses in steelmaking and subsequently have proven valuable in other applications.

Also in the latter half of the 19th century, aluminum and magnesium became important new metals and zinc became widely used for galvanizing steel. The number of metallic elements in use expanded dramatically, and the development of new alloys occurred rapidly to include nearly all the commodity materials in use today.

The same period also saw the birth of the modern chemical industry with the development of aniline dyes (1856), cuprammonium nylon (1857), ammonia soda (1862), dynamite (1866), contact sulfuric acid (1875), and indigo (1878), as well as the first plastic material, celluloid, made from soluble guncotton and camphor. As industry moved from small shops to large-scale production, the chemical industries grew in response to the multitude of new chemical treatments essential to develop new technologies.

The electrical and electronics industries had their early beginnings in the 19th century, with the invention and development of the telegraph (1837), hydraulic power generator (1840), dynamos (improved in the mid-1860's), the telephone (1876), the light bulb (1879), x rays (1895), radiotelegraphy (1895), and the cathode-ray tube (1897). These industries in turn created new materials demands that could only be met by improved scientific research, manufacturing developments, and processing technologies.

An important event that has shaped modern industry—development of the automobile—also took place in the late 19th century, with an electric car (1879), followed by the Daimler

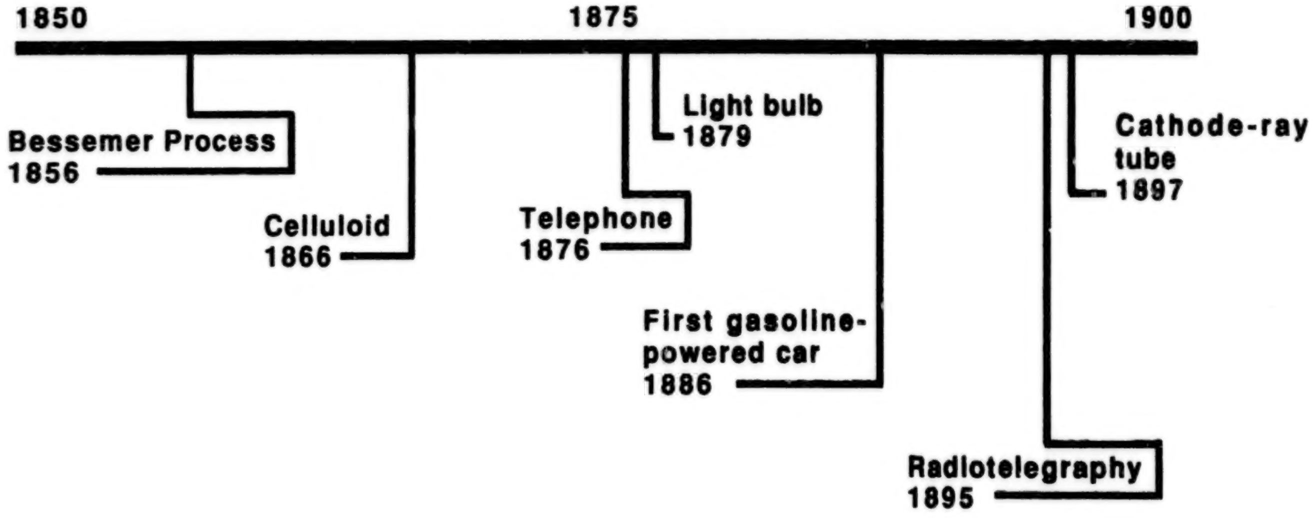


Figure 2-2. The Birth of the Industrial Society (1850 to 1900)

Source: Light and Shadow: The Two Aspects of the New Materials Business, Industrial Bank of Japan, August 1986.

(1883) and the first gasoline-powered car (1886).

Just as the first half of the 19th century set the stage for the use of chemical energy for manufacturing, the second half set the stage for today's industry, which is based on use of commodity materials and assembly line methods.

EARLY MODERN INDUSTRIAL SOCIETY (1900 TO 1950)

The 20th century began with a multitude of materials unavailable just 50 years before and with a rapidly growing body of knowledge regarding the structure of matter and the nature of energy. Following on the burst of mechanical and electrical inventions of the previous half century, industry expanded rapidly in transportation, electronic communications, and polymer chemistry. Petroleum became the energy source of choice for many purposes, with coal relegated to power generation and steelmaking.

Mass production on an assembly line, where a product is assembled in a number of steps, with each worker completing only one of the steps, was conceived by Henry Ford, who began assembly line production of automobiles in 1911 (see Figure 2-3). The concept rapidly spread to most other manufacturing processes.

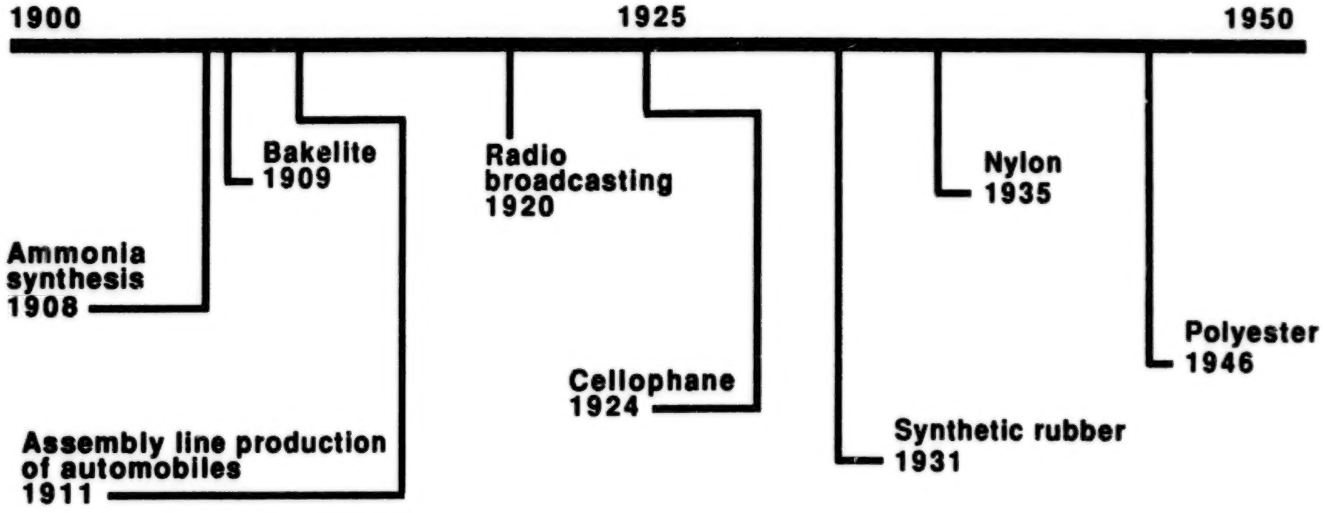
The beginning of radio broadcasting in 1920 and subsequently television broadcasting in the late 1940's led to mass production of receiver sets using the assembly line concept. Mass production brought prices to a level affordable by millions and revolutionized communications and the flow of information. These events led to substantial gains in productivity and economic output, thereby dramatically raising the standard of living in the industrialized nations.

The first major change in materials use patterns since the development of mass-produced steel began soon after the turn of the century. Ammonia synthesis (1908) led to the development of a succession of new plastic materials that began replacing wood, metals, paper, and glass. These included bakelite (1909), cellophane (1924), synthetic rubber (1931), nylon (1935), melamine (1937), polyethylene (1938), and polyester (1946). These new materials were largely derived from petroleum, which was a relatively inexpensive source of organic chemicals.

The structure of industry in the first half of the 20th century was characterized by the following features:

1. Mass production on an assembly line basis using interchangeable parts.

Figure 2-3. Early Modern Industrial Society (1900 to 1950)



Source: Light and Shadow: The Two Aspects of the New Materials Business, Industrial Bank of Japan, August 1986

2. Use of abundant, cheap energy in the form of petroleum products and coal-generated electrical power.

3. Importation of a large portion of the necessary raw materials at relatively low prices to manufacture high value-added products for domestic use and for export.

4. New product development based on discovery and invention—for example, television, penicillin, synthetic rubber and polymeric materials, organic insecticides, nuclear fission, transistors, and computers.

5. Product design geared to available commodity materials, with performance limitations being functions of materials properties.

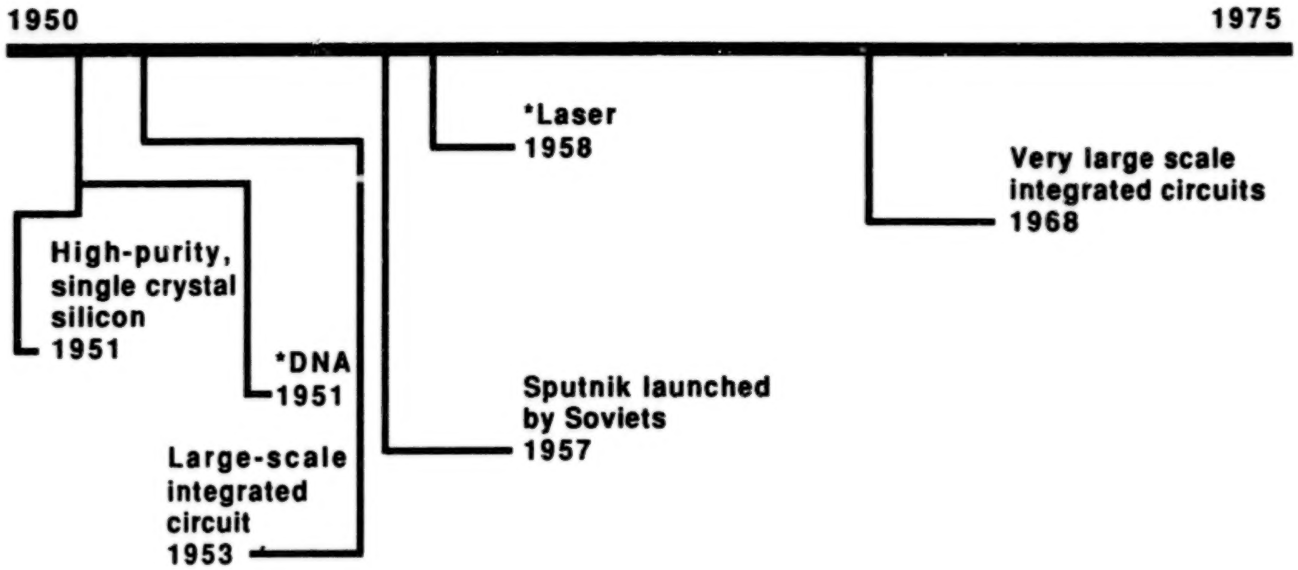
The last point is particularly important because one key difference between materials developed in the past and the advanced materials of the 1980's is that manufacturers now develop the material to satisfy design and performance requirements rather than limiting the design and performance criteria to the materials. In the past, changes have tended to be incremental; and the concept of developing new materials in response to performance requirements has not been pervasive until recently.

A notable exception to the above generalization was the development of nickel-based and cobalt-based superalloys, which could well be called the first of the modern advanced materials. After development of the first practical jet engine in 1939, it was realized that the full potential of the new engine could not be attained with existing metals; new alloys were needed to withstand the high temperatures, stresses, and corrosive environments of the jet engine. The superalloys were thus developed in response to a performance requirement that could not be met by an existing material. Improvements are still being made in superalloy turbine blades by directional solidification and single crystal investment casting.

MODERN INDUSTRIAL SOCIETY (1950 TO 1975)

The advanced materials phenomenon of the 1980's was prompted by a sequence of events associated with World War II, the space race which began in the 1950's, and the 30 years of industrial expansion which followed the war. During the war the issue of strategic and critical materials became immediately obvious. This issue prompted legislation such as the Strategic and Critical Materials Stock Piling Act of 1946 and the Defense Production Act of 1950. Research to develop substitute materials,

Figure 2-4. Modern Industrial Society (1950 to 1975)


1950
1975
High-purity, single crystal silicon 1951
*DNA 1951
Large-scale integrated circuit 1953
Sputnik launched by Soviets 1957
*Laser 1958
Very large scale integrated circuits 1968

*Supplemental data, NCMC

Source: Light and Shadow: The Two Aspects of the New Materials Business, Industrial Bank of Japan, August 1986

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particularly plastics and improved synthetic rubber, was also undertaken.

The military demands on communication, detection, and navigation devices spurred electronics research; and research and development of nuclear weapons, and subsequently civilian nuclear power, created new demands on materials and processes. Research capabilities were highly developed during that period at the Atomic Energy Commission laboratories (now the national laboratories of the Department of Energy).

Also, in recognition of the importance of the basic research capabilities of the university system in the United States, research funds were provided by the National Science Foundation (begun in 1950) and other Federal agencies in increasing amounts. The same developments were taking place in the other industrialized nations at the time.

Discovery of the field effect transistor phenomenon in 1947 (see Figure 2-3) and development of methods for making high-purity, single crystal silicon in 1951 (see Figure 2-4) ushered in a new era in communications, process control for automation, and research instrumentation. The development of the large-scale integrated circuit in 1953 was followed by the very large-scale integrated circuit in 1968, which are the forerunners of the ultralarge-scale integrated circuits being developed today. These devices made possible the development of high-speed, high-capacity computers and other solid-state electronics that enabled scientists and engineers to solve problems previously thought too complex to tackle.

The Soviet launching of Sputnik in 1957 triggered the "space race" which became the policy driver for U.S. science and technology issues. The development of space exploration put demands on devices and materials systems to withstand conditions that were never before envisioned.

The period was also a time of rapid development of new consumer markets for a postwar society hungry for an ever-expanding array of products. The world economy was changing in ways that would alter forever the established patterns of trade and commerce. Materials systems and their end-use products were an important component of that change.

With the notable exception of such advances as the discovery of the structure of deoxyribonucleic acid (DNA) in 1951 and the invention of the laser in 1958, this period was not so much a time of breakthrough and discovery as it was a time of scientific refinement. Materials science benefited from developments in other fields with such inventions as the ion microscope in the early 1950's, which allowed scientists to glimpse the atomic building blocks of materials. The ion microscope and other similar inventions greatly expanded the understanding of the structure and behavior of matter, and introduced the possibility of constructing new materials, atomic layer by atomic layer, in effect engineering their properties to suit a given application.

THE NEW MATERIALS SOCIETY (1975 TO PRESENT)

The ability of the Organization of Petroleum Exporting Countries (OPEC) oil cartel to increase crude oil prices during the 1970's created a demand for more energy-efficient equipment and manufacturing processes. This in turn created the demand for new materials exhibiting better weight-to-strength ratios—especially in transportation systems.

Though the availability of fossil fuel energy is adequate to sustain industrial and domestic needs at present, the long-range need to develop new energy sources remains. New processes for production of energy—coal gasification and liquefaction, solar conversion, nuclear fusion, magnetohydrodynamics, and geothermal—are creating even more demanding materials requirements, as is the ever more inhospitable environment in which conventional petroleum products are being produced.

The developing nations have increased their production capabilities in the traditional basic industries. Until recently the industrialized nations, notably the United States, Japan, and the European Economic Community, were able to maintain a competitive advantage by importing raw materials and oil from less industrialized nations and converting these to manufactured products for domestic use and export. The trend over the past 20 years has been for developing nations to develop their own production capacities in basic industries such as steel, aluminum and other metals, cements, ceramics, chemicals, and plastics, with the result that these commodity materials can be imported by the industrialized nations at prices lower than those of domestic materials. In this way the developing nations capture the additional value obtained from the processing of the basic materials.

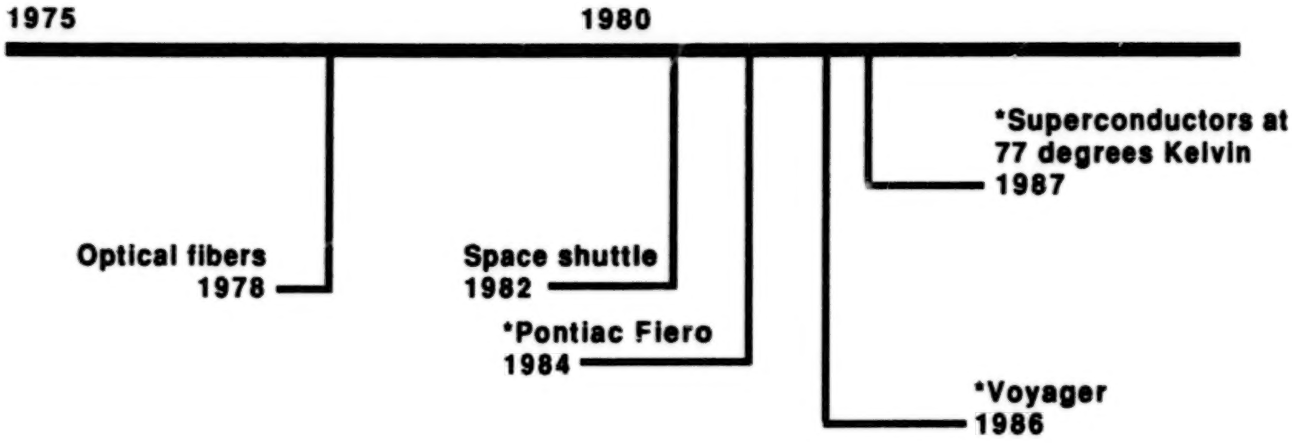
The industrialized nations are establishing new, knowledge-intensive, high-technology industries, using, in many cases, inexpensive raw materials to produce high value-added products with superior properties and new uses.

In addition to the above developments, rapid advances in the medical sciences, coupled with availability of new materials, have created a potentially large market for new materials for medical and dental prostheses and for sophisticated diagnostic equipment. These developments have combined to bring about a fundamental shift in the structure of the world economy.

Among the first to understand the implications of these changes in industrial structure for the future of their domestic economy were the Japanese. Convinced that the Japanese economy had attained par with Western nations, Japan, as far back as the early 1960's, began extensive planning for the future and produced an outline in the form of a white paper, "Road to an Advanced Nation." By 1981, the Ministry for International Trade and Industry had formulated a detailed policy, based on a solid consensus with Japanese industry, for development of a technology-based country. The emphasis was, and continues to be, on new materials, such as high-performance structural alloys, ceramics, polymers, and composites, and on a wide variety of electronic, magnetic, and optical devices.

The United States and other Western countries have lost the competitive edge to the Japanese in certain areas such as electronics. In some areas the United States maintains a competitive advantage, particularly in polymer composites, although that industry is largely transnational and the carbon fiber market is dominated by the Japanese. Western European countries are also strong competitors in certain advanced materials. The less developed materials, such as alloys, structural ceramics, and composites, constitute the competitive arena today.

Figure 2-5. The New Materials Society (1975 to Present)



*Supplemental data, NCMC.
Source: Light and Shadow: The Two Aspects of the New Materials Business, Industrial Bank of Japan, August 1986.

As shown in Figure 2-5, the important technical events of the period have included such milestones as the development of practical optical fibers (1978) and the space shuttle (1982).

The 1980's have seen many achievements in new materials technology. These include shape memory alloys (alloys of titanium and nickel and other metals), new engineering polymers (especially the polymer composites), and fine ceramics. These new materials have led to important applications such as the Pontiac Fiero (first built in 1984) with polymer alloys replacing metal on much of the automobile (except engine), composite airplanes, such as the Voyager, which circled the Earth without refueling in 1986, and the first Federal Aviation Administration-approved general aviation airplane (Beech Aircraft's Starship), and ceramic turbochargers on some automobiles. But, perhaps the most important new development in ceramics has not been in structural materials but in the area of ceramic superconductors which first demonstrated superconducting characteristics at temperatures achievable with liquid nitrogen cooling systems (77°K) in 1987.

WHAT THE FUTURE HOLDS

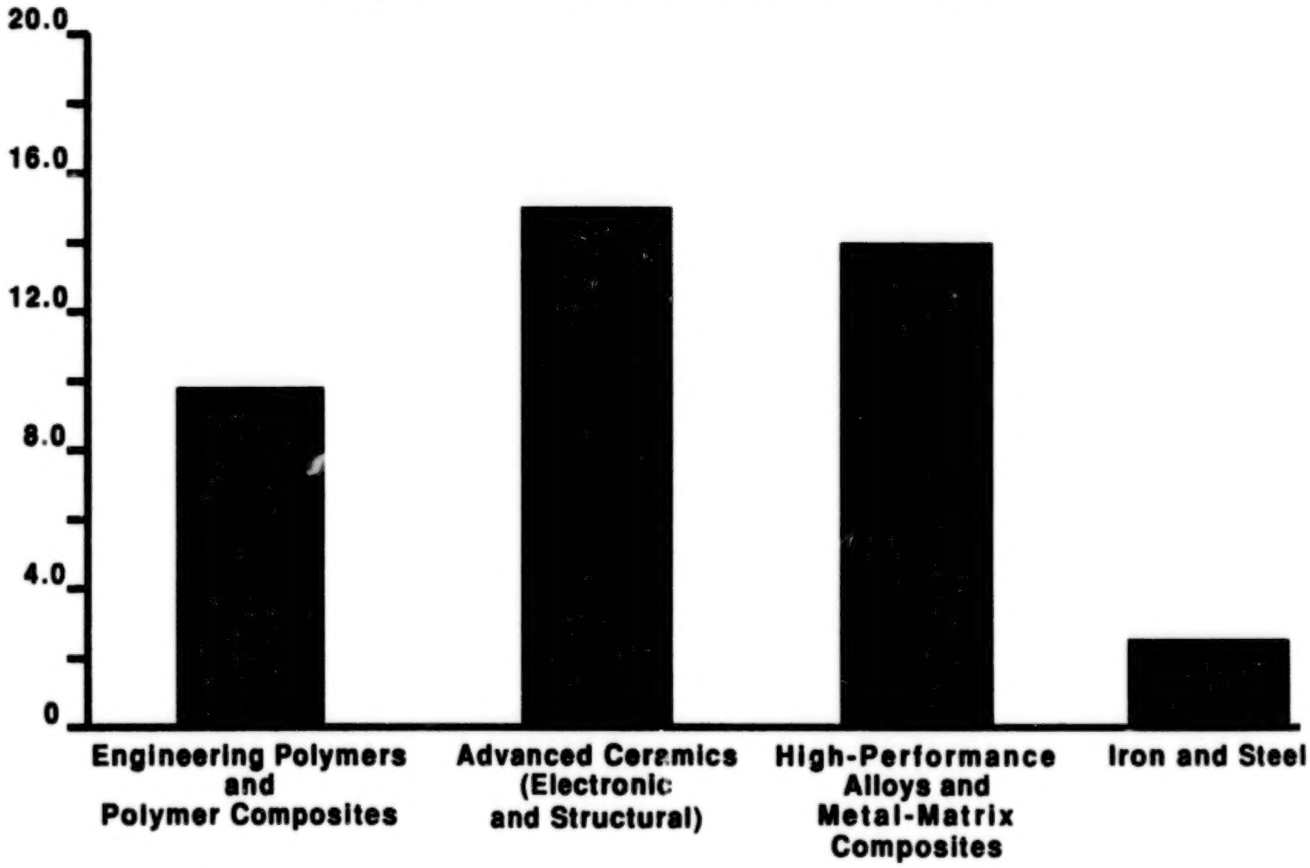
As Figure 2-6 indicates, according to Bureau of Mines sources, the growth of advanced materials will be substantial over the next several decades. The growth estimates range from 8 to 16 percent per year depending upon the materials category. A portion of the projected growth of advanced materials will result from their substitution for conventional materials, while the remainder will be the result of new uses for these materials. The growth rate for iron and steel, by comparison, is projected to be at or below that of the economy in general.

The estimates for future advanced materials markets vary depending on the source of the estimate. Informed estimates by the Bureau of Mines predict a world market around $100 billion annually by the early 21st century for all of the advanced materials groups combined, with about half of that market in the United States alone.

Various factors will affect the market penetration of these materials. The rate of growth of a specific material will be higher if the material offers a substantial increase in a performance parameter or is an enabling technology with application across a broad range of end-uses. If, on the other hand, the material offers only marginal improvements in performance, or is of a highly specialized nature, the growth rate will be substantially slower.

Serendipity plays an important role in the development of new materials technologies and innovations. For example, the new "high temperature" ceramic superconducting materials mentioned above open up new possibilities in computers, transportation, and energy storage and transmission. However, there are still obstacles in terms of materials fabrication and

Figure 2-6. U.S. Advanced Materials and Iron and Steel Compound Annual Growth Rate from 1985 to 1995



Sources: Business Communications Co.; Bureau of Mines

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the ability of the material to transmit the needed current density. These problems could prove to be insurmountable or they could be solved in a relatively short time. Depending on the outcome, the future of these new materials systems could vary greatly. Such uncertainty is always present when government and corporate decisionmakers attempt to design policy for the future. Policy must, therefore, remain flexible in order to respond to unanticipated events.

SUMMARY

In summary, the advanced materials phenomenon of the 1980's differs from previous materials development in the following ways:

1. The rate of new materials development is greater than ever before, accelerated by technology and competitive pressures in a world market.

2. Molecular engineering of materials makes it possible to create new materials for specific properties and uses rather than simply modifying existing materials; this provides opportunities to redesign parts and processes to take advantage of new materials performance characteristics.

3. A much wider range of scientific expertise is required, and designers, engineers, and assembly line workers must work with materials scientists at all stages to ensure product reliability at minimum cost.

While estimates for specific materials systems vary in terms of future growth, most experts agree that the growth of advanced materials systems in general will be substantial. The next part examines more closely these new materials systems, their uses and classifications, and the technical challenges that face their development.

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PART III

ADVANCED MATERIALS—TECHNICAL CHARACTERISTICS AND CONSTRAINTS

In general, advanced materials exhibit greater strength; higher strength/density ratios; greater hardness; and/or one or more superior thermal, electrical, optical, or chemical properties when compared with traditional materials currently used in large-volume assembly line production. Advanced materials are produced from metals and alloys, ceramics, polymers, and composites of these three material types. While the technical challenges for the production of these materials are many, the potential rewards are also great.

DEFINITIONS AND QUALIFICATIONS

Scientists, engineers, economists, production personnel, industrial leaders, and salespersons all have different perspectives on advanced materials, and each necessarily categorizes materials and processes according to particular needs. In general, advanced materials exhibit greater strength; higher strength/density ratios; greater hardness; and/or one or more superior thermal, electrical, optical, or chemical properties when compared with traditional materials currently used in large-volume, assembly line production. They are materials with property values previously unknown or unavailable, with the potential for commercialization as new products for new uses or replacement of existing materials.

Further qualifications are necessary to distinguish the new advanced materials from former advanced materials:

1. They are likely to require advanced and sophisticated processing to attain the necessary purity levels and physical characteristics needed for use by high-technology industries.

2. Fabrication technology is, in most cases, the major technical barrier to commercial application. Early stages of development involve redesign, retooling, and new process development to ensure uniformity, high yield, and reliability so that extensive capital investment and long development times are required. Production, at least in early stages, is typically done by batch processing and is, therefore, labor intensive. Other diseconomies resulting from a low-scale operation typically mean a high unit cost. New materials usually find initial application in high value-added products such as aircraft, electronics, and medical materials and devices.

3. There is an increased need for materials disciplines to work together from the design stages through the manufacturing stages. In some cases, the material may be developed to satisfy design requirements. In other cases, the design must be adapted to the properties of the material. A continuous matching of design to material property must take place in order to produce optimum properties and performance.

4. There is intense competition not only between advanced materials and traditional materials but also among new materials for any given application. The pace of new materials research and development is so rapid that multiple candidates may be available for a single application. There is, therefore, considerable risk and uncertainty in advanced materials development, with the corresponding potential for high reward.

CLASSIFICATION

Advanced materials can be classified on the basis of the type of material (metal, semimetal, ceramic, polymer, composite, or combination); the function of the material in a given use (structural, electronic, optical, magnetic, biocompatible) and the properties which make it suitable for that use (such as strength, corrosion resistance, heat resistance, semiconduction, light-electricity conversion, and high magnetic-field strength); or the process technology applied to the material (such as powder metallurgy, hot isostatic pressing, single crystal growth, and molecular beam epitaxy). The classification used for this report is based on four materials types which are augmented further by two functional categories, as indicated below:

1. Metals and alloys
2. Structural ceramics
3. Engineering polymers
4. Advanced composites
5. Electronic, magnetic, and optical materials
6. Medical and dental materials

The mixing of materials types with functional categories is justified by the radically different attributes that are required for a material in the first four categories as compared to the latter two. The first four categories are structural uses, while the latter two are device oriented. Each of the six major categories is discussed in general terms in the following section.

(A detailed listing of advanced materials and devices, as developed by the Bureau of Mines, is found in the appendix. The chemistry and forms, processing methods, critical properties, and actual or potential uses, are indicated in the listing.)

PROPERTIES AND FUNCTIONS OF THE SIX TYPES OF MATERIALS

Metals and Alloys

Intensive research and development is being done to improve the properties of metals and alloys, to develop new alloys with superior properties, and to find new uses for existing alloys. The following are some of the more important materials and processes: directionally solidified, single crystal, and coated superalloys; aluminum-lithium alloys, with lower density and

Nickel- and cobalt-based superalloys have been important in the development of jet aircraft engines, such as those used in the F-16. These engines also use large amounts of high-technology metals such as titanium. Tantalum and columbium are also present in these materials systems, as well as more conventional metals such as aluminum, chromium, and manganese. (Photograph courtesy of U.S. Air Force)

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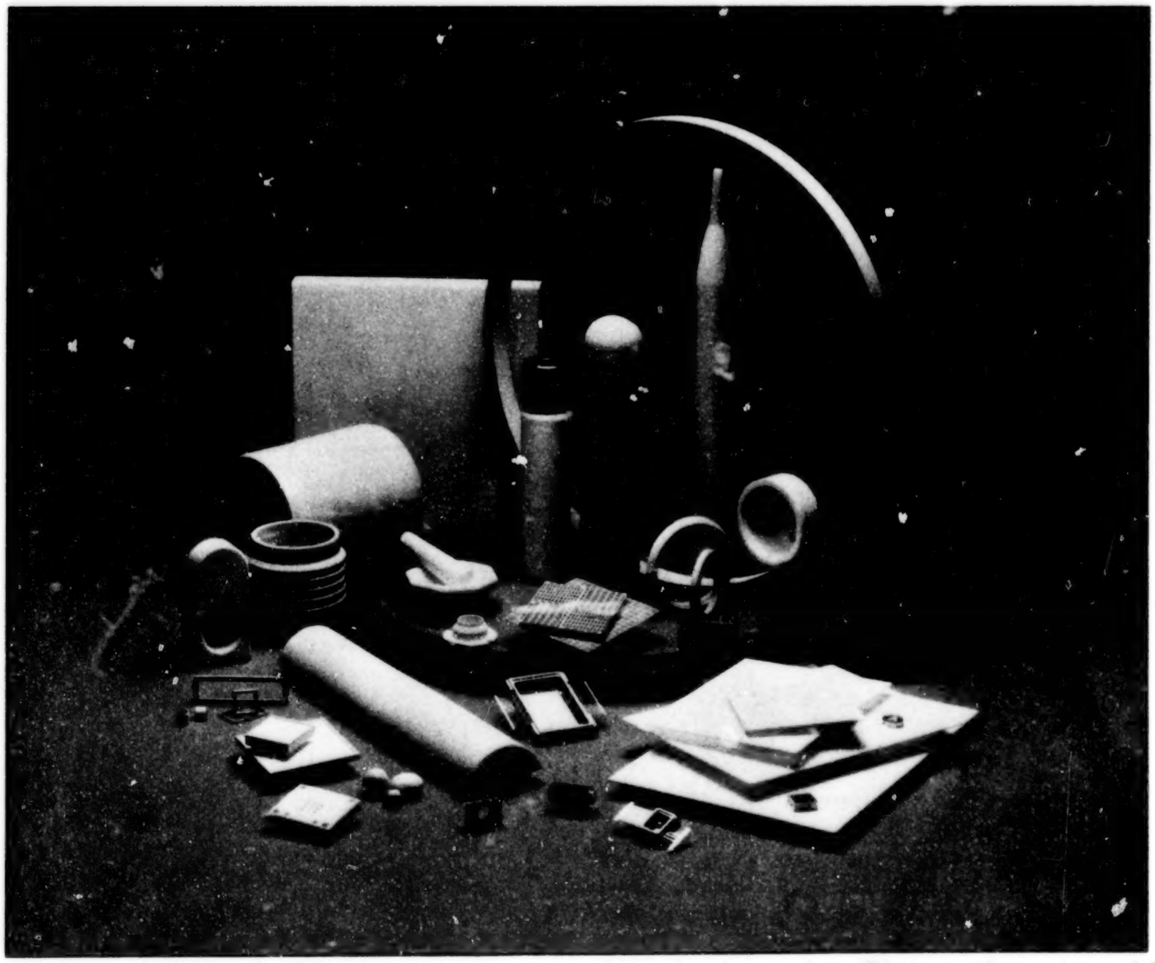
greater strength than other aluminum alloys; amorphous alloys with superior strength and magnetic properties; rapidly solidified alloys with new compositions and microstructures; superfine particles for improved powder metallurgical processing; ordered intermetallics with improved strength and corrosion resistance; magnetic alloys with greatly improved energy product and coercive force; superconducting alloys for high-intensity magnets; shape memory alloys for clamps, rivets, sensors and accoutres, orthodontic wire, and potentially for kinetic energy storage devices; porosity metals for electrodes, filters, and catalyst carriers; superplastic alloys suitable for new forming processes; improved titanium alloys and coated alloys with greater oxidation resistance; beryllium-copper alloys with high thermal conductivity and fatigue resistance; and new methods of thermal hardening and thermochemical coating of metals to provide greater resistance to heat, wear, and corrosion.

Improvement of existing alloys, such as new high-strength steels, particularly in development of new microstructures, is an important factor in materials competition. Substitution of polymer and ceramic materials for metals likely will be a gradual process because of the technical and economic problems of developing new manufacturing processes.

Structural Ceramics

These materials, by virtue of their generally superior heat resistance, wear resistance, and corrosion resistance, are potentially important materials for use in turbine engines, adiabatic engines, cutting tools, wear parts, and many other applications in which they would replace metals. They are made typically by producing uniform, submicron powders which are then formed and sintered by a variety of high-temperature methods, with or without pressure.



This photograph shows some of the many possible uses of structural ceramics. (Photograph courtesy of Coors Ceramics Company)

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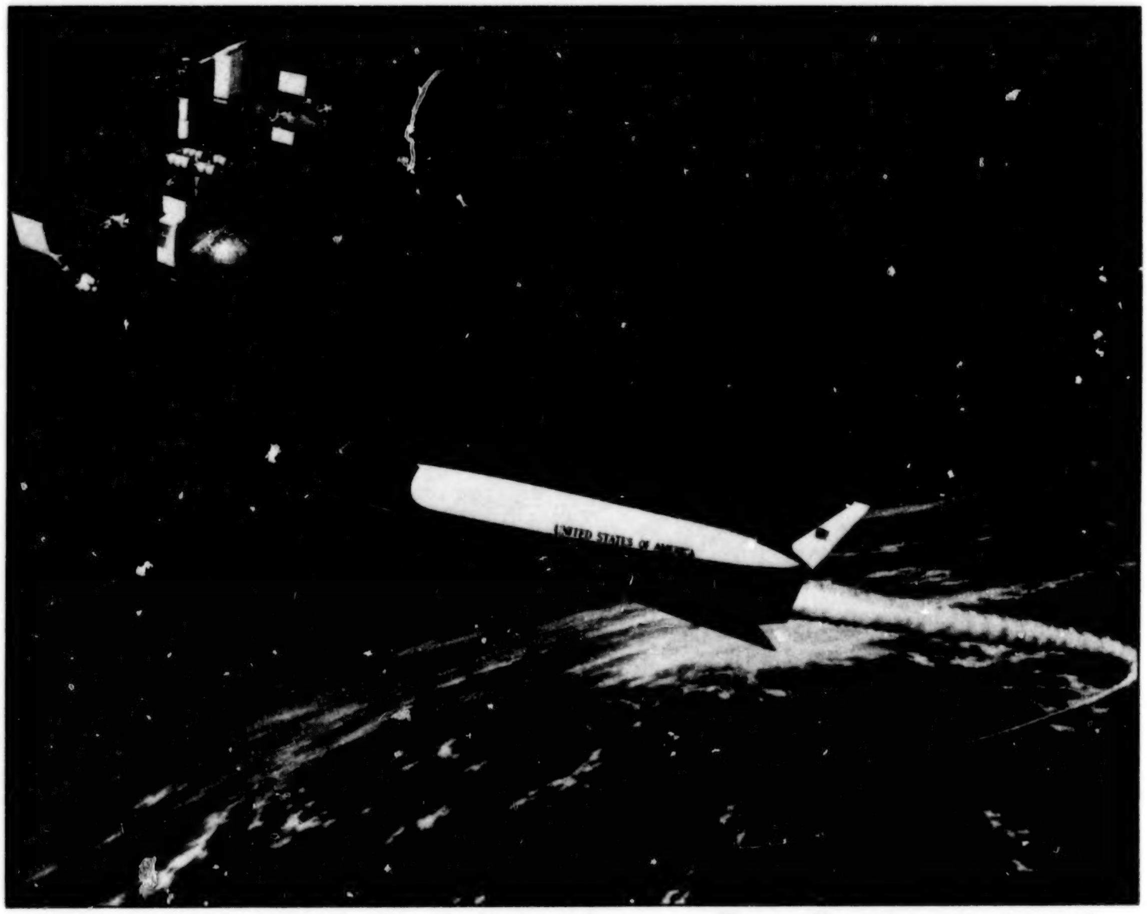
They are also made as particles, whiskers, and fibers for reinforcement of ceramic, metal, and polymer composites and may be applied by a variety of methods as coatings on metal or ceramic parts to impart heat-resistant properties. Projections of very rapid growth over the next 20 years have been made, but there is much uncertainty regarding solutions to technical problems, notably the inherent brittle fracture of ceramic materials. The acceptance of new materials and the concomitant requirements for redesign and retooling also can have an impact on growth. The competitive pressure from Japan is very strong, however, and U.S. industry will necessarily continue development of structural ceramic materials.

The important materials for structural ceramics are alumina, partially stabilized zirconia (with calcium, magnesium, or yttrium oxides), tetragonal zirconia polycrystal, silicon carbide, silicon nitride, sialons (solid solutions of silicon nitride and alumina), boron carbide, aluminum nitride, beryllia, cordierite, boron nitride, titanium diboride, titanium carbide, titanium nitride, yttria, and thoria. In general, the raw materials for these materials are abundant, with the possible exception of yttria. The critical factor in development of large-scale production, however, is the processing capacity for the high-purity, submicron powders.

Engineering Polymers

Though plastics, such as polyethylene, polypropylene, polystyrene, and polyvinyl chloride, have constituted a major industry for many years and fiberglass-reinforced plastics have found broad application, a new class of polymeric materials with exceptional strength and heat resistance is emerging and is being used increasingly in automotive, aircraft, and many other applications replacing metals. To distinguish the new materials from the widely used "commodity" materials, the terms "engineering polymers" and "performance polymers" are used. Among those generally called



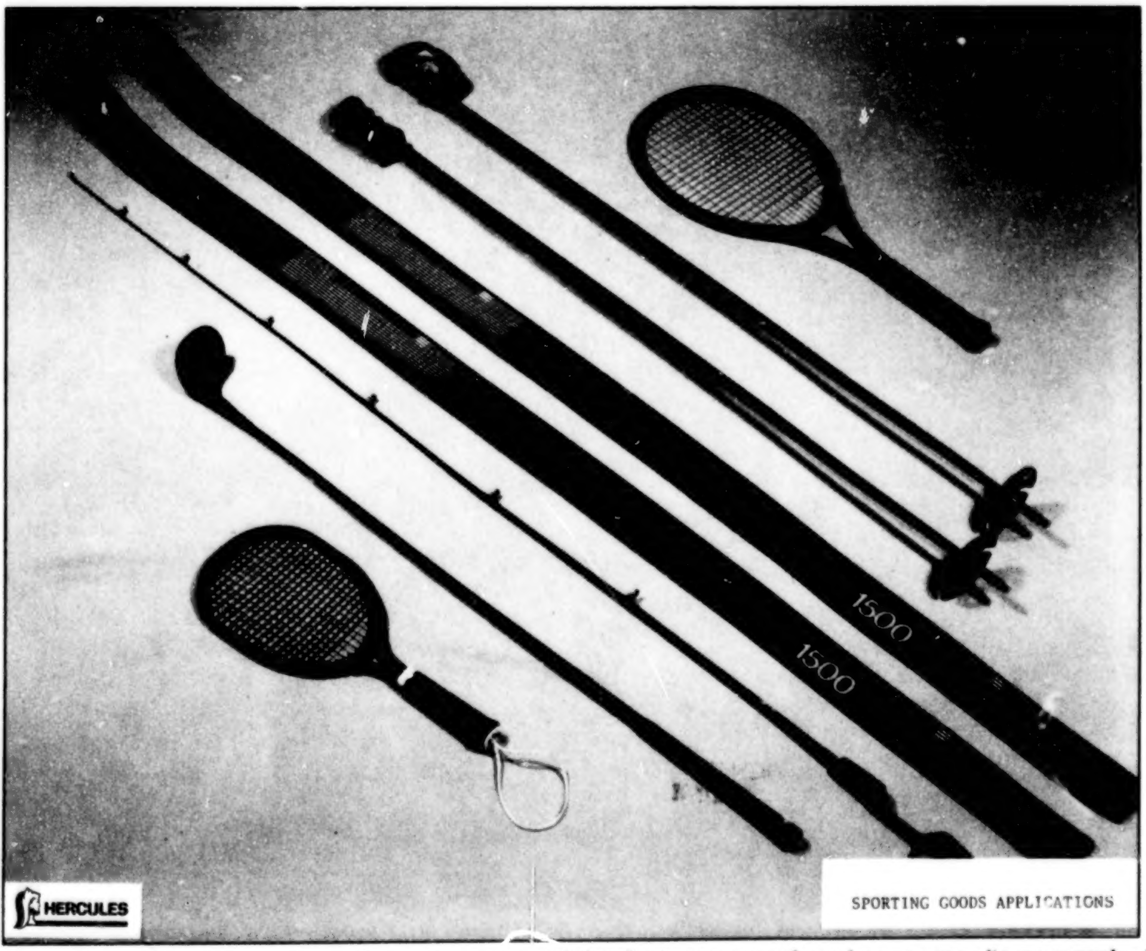
Because of optimal weight-to-strength ratios, the National Aerospace Plane will employ many types of engineering polymer systems. (Photograph courtesy of Suppliers of Advanced Composite Materials Association) engineering polymers are polyphenylene oxide, polybutyl terephthalate, polyethylene terephthalate, polyacetal, polycarbonate, and alloys and blends of these polymers. The new generation of performance polymers, with decomposition or glass transition temperatures as high as 530°F, include fluoro-polymers, polyamide-imide, polyarylate, polyetheretherketone, polyether-imide, polyethersulfone, polyimide, polyphenylene-sulfide, and polysulfone. These materials, reinforced with a variety of fibers, are being applied to both exterior and interior components of aircraft and are being evaluated for use in automobiles to replace sheet steel in the body and possibly as structural components. High growth rates are anticipated.

Extensive research is being conducted on use of polymer materials for electrical conductors, semiconductors, electromagnetic interference shields, optical fiber, and optical switching devices. With the intense interest in optoelectronics, polymers may be in direct competition with metallic and ceramic materials in many applications.

In addition to fibers for composites, many metallic and nonmetallic materials are included in polymers as fillers, pigments, opacifiers, and modifiers. The development of new engineering polymers will have a large effect on use patterns in these materials.

Advanced Composites

The need for stronger, lighter weight, more heat-resistant materials for a wide variety of applications has spurred research and development of metal matrix, ceramic matrix, and polymer matrix composites containing particulate, whisker, and fiber reinforcements. New fibers of carbon, boron, silicon carbide, silicon nitride, alumina, zirconia, aluminum silicates, and polymers have broadened the range of materials and properties to be investigated.

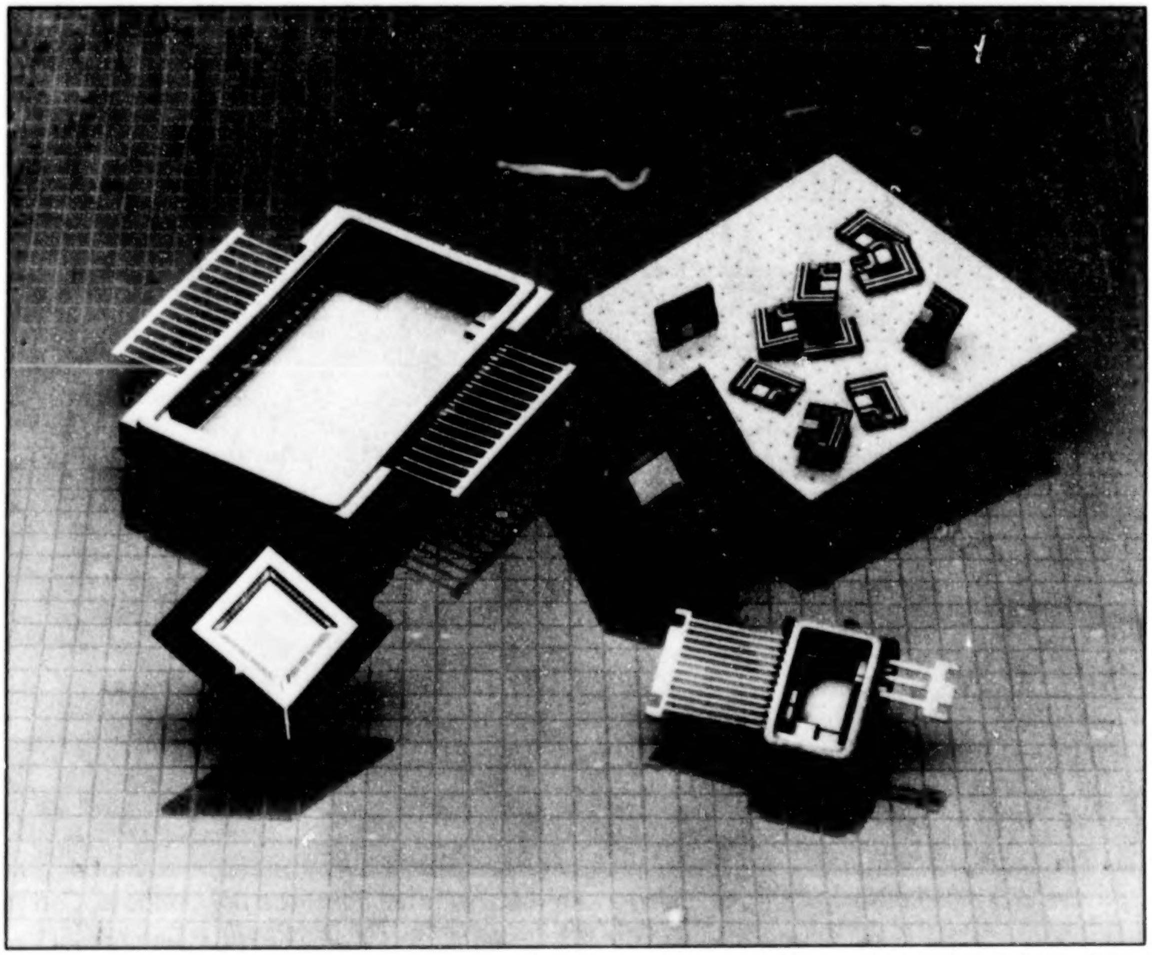


Sporting goods, such as those shown here, are some of the first mass-produced consumer items employing advanced composite systems. (Photograph courtesy of Hercules Incorporated)

Reinforcement of ceramic materials to change the mode of failure from catastrophic and unpredictable to gradual and predictable is considered essential for successful commercialization of ceramics in automotive and aircraft engines. The development of carbon matrix-carbon fiber composites for use as the skin of the proposed National Aerospace Plane will permit repeated reentry at very high temperatures and offers the promise of widespread application in the space program, particularly the orbiting space station project.

Electronic, Magnetic, and Optical Materials

In general, these materials form the basis of a mature, but very rapidly changing, industry. The composition of these materials covers a large portion of the periodic table and will require appreciable amounts of relatively rare materials, many of them byproducts of commodity metals production, including gallium, germanium, indium, bismuth, yttrium, lanthanum, and the rare earth elements. Advanced ceramic fabrication, single crystal growth, chemical vapor deposition, trace level dopant diffusion, molecular beam epitaxy, fiber pulling and modification, and many other techniques are employed to make numerous electronic, optical, and magnetic devices. Among these are semiconductors, vibrators, oscillators, filters, transducers, spark generators, thermistors, solar cells, solid electrolytes, oxygen sensors, pH meters, temperature sensors, gas sensors, humidity sensors, lasers, light memory elements, video display and storage systems, capacitors, ferrite recording tape, laser diodes, light-emitting diodes, electro-optical and acousto-optic sensors, optical communication fibers, and most recently, ceramic superconductors, which are expected to revolutionize electronics and electromagnetics.



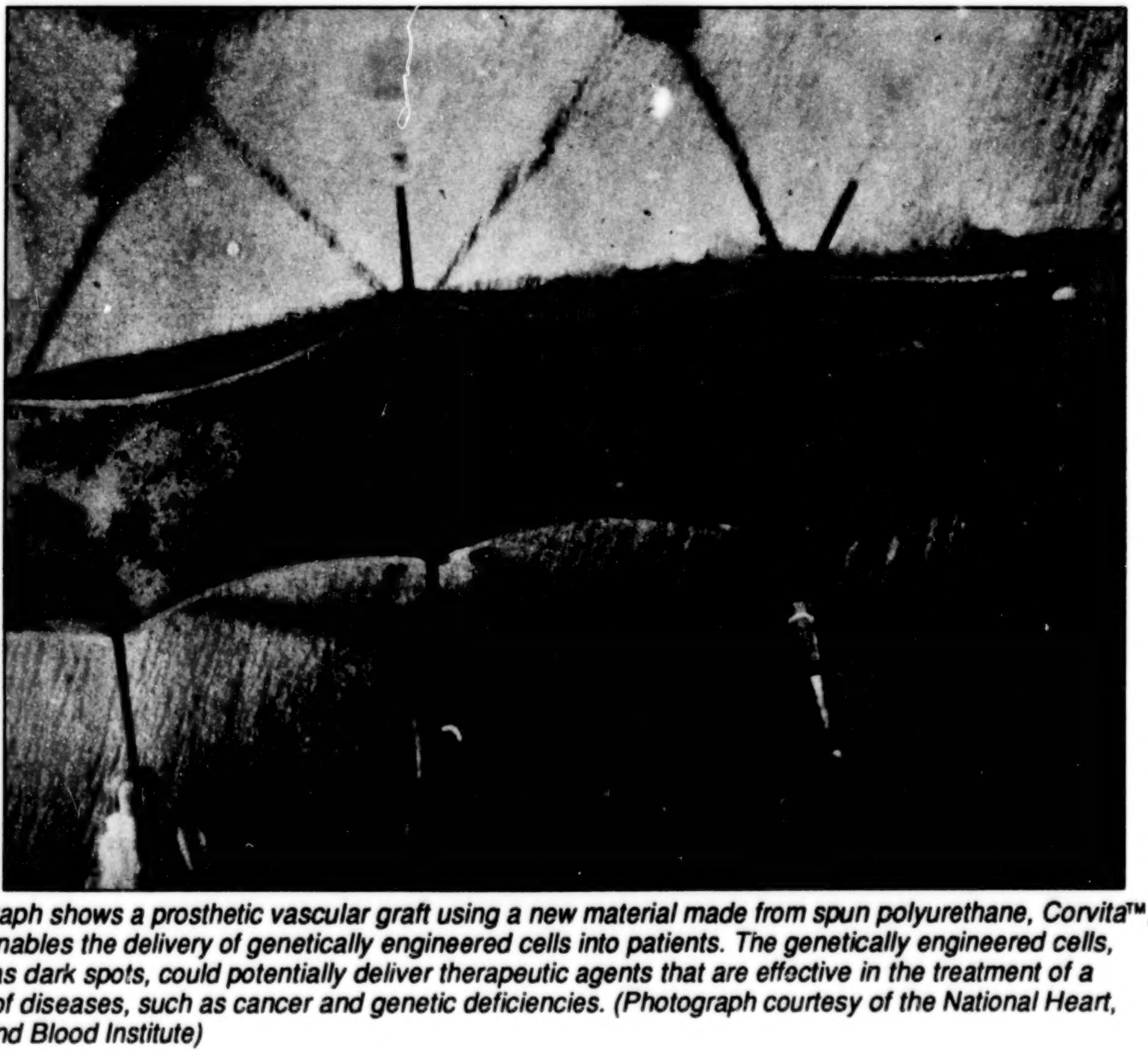
Electronic equipment, such as the multilayer ceramics fiber optic transmitter package shown here, is one of the strongest markets for advanced materials. These products employ advanced ceramics. (Photograph courtesy of Coors Ceramics Company)

Medical and Dental Materials

Uses of alumina and calcium phosphate glasses as prosthetics for bone replacement and dental crowns and use of tantalum and other nonreactive metals for joint replacements are well-established businesses which are expected to continue to grow at a rapid rate. Use of metallic superconductors for high-field magnets for magnetic resonance imaging is also increasing rapidly because of the value of the diagnostic method. Because raw material and production costs of these materials and devices are considered minor compared to the benefits, research is being intensified to develop new prosthetic materials and diagnostic equipment. New tissue and skin replacement materials, carbon fiber-reinforced polylactic acid for tendon replacement, silicones and resins for artificial blood vessels and replacement organs, and new ceramic and metallic materials for bone and teeth replacement are expected over the next few years. Discovery of the new high-temperature ceramic superconductors may reduce the costs of magnetic resonance imaging equipment and result in an accelerated growth rate. The medical and dental fields are changing so rapidly that it is difficult to predict changes in materials use patterns.

TECHNICAL CONSTRAINTS

Because the aforementioned classes of materials have quite different properties, will be usable in different environmental ranges, and are at different stages of technological maturity, each offers a unique set of problems to be solved before successful commercialization can occur. Some of these problems are summarized later. In spite of the differences, however, there are several problem areas common to the new materials.



Photograph shows a prosthetic vascular graft using a new material made from spun polyurethane, Corvita™, which enables the delivery of genetically engineered cells into patients. The genetically engineered cells, shown as dark spots, could potentially deliver therapeutic agents that are effective in the treatment of a variety of diseases, such as cancer and genetic deficiencies. (Photograph courtesy of the National Heart, Lung, and Blood Institute)

General Technical Constraints

Structure-Property Relationships: One of the key features of the new materials is that the structures are controlled to obtain optimum properties. In addition to controlling the crystal structures, it is essential that the microstructure, the way in which the crystals are arranged, be controlled. For many materials the level of understanding of the relationships between structures and properties is inadequate, and the relationships between these and processing parameters are only generally understood. Accordingly, a large portion of current research is in this area.

Physical Property Data Bases: Large-volume commodity materials such as sheet steel, copper wire, and so forth, are selected for a particular application on the basis of well-measured and well-understood properties. It is relatively easy to match these materials to specifications because physical property data are readily available. Advanced materials are fundamentally different because they are, in general, engineered for particular designs and applications for which no commodity materials are available. Consequently, physical property data bases, from which a designer or process engineer can select a material with correct specifications, are unavailable. The situation is complicated even more in some cases because two apparently identical materials from different suppliers may not be equally suited for a given manufacturer's needs. Much effort is expended, therefore, in locating a suitable material, and it is necessary for the materials supplier and the manufacturer to work together in order to develop a suitable material. This situation will be ameliorated only when structure-property-processing relationships are adequately understood; only then will many advanced structural materials be cost-competitive with commodity materials in mass production. Standardization of processing and compilation of property data bases need to be given a very high priority in the research and development arena.

Test Methods: Standardized tests for properties of commodity materials have been devised by the American Society for Testing and Materials and can be used worldwide and provide reliable comparisons of competing materials. Such tests are not yet available for many of the new materials; in fact, the only criterion for acceptance of a new material in many cases is successful performance. It is expensive to proof test each component in simulation tests or actual use, so these materials will not be competitive with commodity materials until standard testing methods are developed. Nondestructive evaluation methods are urgently needed, particularly for materials such as structural ceramics in which critical flaws are difficult to prevent and to detect. It is likely that nondestructive evaluation will be needed for each component made of such materials.

Deterioration In Use: All materials will, in general, suffer from deterioration of critical properties during use. The long-term effects of stress, flexure, exposure to corrosive environments, exposure to radiation, and so forth, cause cumulative damage to materials, causing them ultimately to fail. Methods of assessing cumulative damage and predicting remaining usefulness have not been developed for the new materials. It is essential that methods be devised, perhaps for continual monitoring during use, before manufacturers will have enough confidence in the new materials to adopt them.

Processing Science and Engineering: New materials do not lend themselves to assembly line use for several reasons: control of properties during processing is not well understood; the materials cannot be made using existing assembly line equipment; and the low production volumes do not justify large capital expenditures, at least in the early stages of commercialization. Hence, new *structural* materials, in particular, will not be widely adopted until fully integrated design and manufacturing processes and a high degree of automation are developed. It will be necessary, moreover, to begin the process even before all the relevant structure-property-processing relationships are fully understood so that the opportunity to learn by error will be available. Improvements in processing and properties of new materials will be, of necessity, an incremental process.

Joining Technology: To assemble the components of a piece of complex machinery or device, it is normally necessary to bond dissimilar materials, such as ceramic to metal, different alloys to each other, or polymer to metal. Because of differences in chemistry and coefficients of thermal expansion this can be a

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formidable task. If welding, soldering, or brazing media are used, the bond is likely to be the weak point in the structure, nullifying much of the advantage of the new material. If direct bonding between the new materials is possible, the bonding process itself may alter the properties of one or both components. Much research will be needed to overcome these problems. New design concepts will also have to be developed so that mechanical fits can be used to the maximum.

Materials-Specific Technical Constraints

Each class of materials has some unique problems which must be solved before successful commercialization can take place. Solutions to these problems will, in the main, require close attention to the whole materials cycle, from raw materials to recycling or disposal, including attendant costs and environmental effects of each step. The key element is successful exchange of knowledge by research and manufacturing personnel, with that knowledge flowing in both directions. The following are some of the more important problems to be attacked.

Metals and Alloys: In addition to all of the problems addressed above, each type of metal or alloy presents additional concerns. Some rapidly solidified alloys, for example, are composed of metastable phases—that is why they have previously unattainable properties. But metastability is, by the laws of thermodynamics, a temporary state; more information about the persistence of the metastable phases in use is needed, and means of enhancing that persistence need to be developed. Powder metallurgical forming methods provide materials with advanced properties, but forming methods need to be improved, particularly for complex components. Net shape forming methods need to be improved so that final machining is minimized and full density can be attained when needed. Resistance to heat, abrasion, and corrosion of many alloys can be improved by the application of ceramic coatings or by surface hardening by the formation of carbide, nitride, or boride coatings. This can be accomplished by many methods, using many materials. Tribological properties of some metals can be improved greatly by surface treatment, thus reducing wear losses. Research and development in this area would improve the competitive position of metals and would not require wholesale changes in the basic manufacturing methods.

Structural Ceramics: The major impediment to successful application of these materials, with their very high strengths, hardness, and corrosion resistance at high temperatures, is their brittleness. Fracture in a ceramic material originates at flaws—voids, scratches, or inclusions—and proceeds to total failure very rapidly. Much research has been done and considerable progress has been made in controlling flaws, but the rejection rate is very high, as much as 80 percent, and the range of measured strengths in many samples from the same production run is very wide. The dependability and consistency required for mass production has not been attained in most cases. The problem of critical flaw density cannot be solved by overdesigning, as with metals, because only one critical flaw is necessary for failure; and the larger the component is, the more likely it will have a critical flaw. A second major problem with ceramic materials is that the very properties that make them useful, hardness and strength, also make them difficult to fabricate to close dimensional tolerances. Net shape production is difficult because shrinkage during sintering must be uniform and closely controlled. This requires very precise control of processing parameters. They cannot, moreover, be machined to final size and shape by conventional methods. These areas of concern are being actively researched at present, but solutions, which must be found for these materials to be competitive, appear to be several years away.

Engineering Polymers: Remarkable strides have been made in development of new heat-resistant polymers over the past few years and it seems likely that the state of knowledge is at a level sufficiently high to ensure even more advances. The major problems to be solved for existing materials, in addition to the aforementioned, are development of better methods of controlling surface finish, new surface coatings, and better fillers and colorants. New methods for repair of damaged components need to be developed, and components need to be designed for repairability. The growing problem of solid waste disposal and the chemical resistance of polymer materials requires that serious technical effort be given to designing for recyclability and that cost evaluations include

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disposal and recycling costs in the materials cycle.

Advanced Composites: All three classes of composites, metal matrix, ceramic matrix, and polymer matrix, are handicapped by inadequate understanding of the forces operating between the matrix and the reinforcing materials (fibers, whiskers, or particles). Much research will be required to maximize the effects of reinforcement. Fabrication is complicated by the requirement for uniform, predictable, and controllable distribution of the reinforcing phase and by the labor-intensive nature of the lay-up of materials. Considerable research is needed to make it possible to control and vary curing times so that a range of forming methods can be used for a given polymer material, and production rates can be accelerated.

Electronic, Magnetic, and Optical: The myriad of materials, devices, and combinations of these materials and the rapid development of new knowledge makes generalization about research needs nearly impossible. Current trends are toward further miniaturization, more complex devices consisting of electronic and optical circuits in combination, and a new generation of sensors and emitters. The potential payoff for these materials and devices is so great that the generic problems associated with structural materials (such as high cost and the need for automated manufacturing) generally do not apply; and the research effort is enormous. Miniaturization is limited at present by the need to remove heat from the circuitry; therefore, materials with high thermal conductivity, such as aluminum nitride and diamond films, are being developed. The renewed interest in superconducting electronics may lead ultimately to very high-speed, ultralarge integrated circuits in which no heat is generated. The use of high-critical-temperature ceramic superconductors for this purpose appears to be the first large-scale application. Much research is under way around the world. Optical systems may be improved greatly with the development of ever more transparent fibers now being studied.

Medical and Dental Materials: Research progress in this field is very rapid, and the application of new materials is nearly independent of cost. In addition to developing and testing new materials, evaluation of long-term durability is a high-priority concern.

SUMMARY

Advanced materials constitute a wide range of material systems. It would be erroneous to attempt to define these systems without emphasizing the dynamic and interrelated nature of advanced materials forms and their functions. This complexity presents challenges to those who seek to develop a consistent taxonomy and for those who attempt to design policy. Systems designers and engineers who attempt to develop optimal physical properties, given economic and technical constraints, are also faced with a complex array of options.

This level of complexity requires a high level of cooperation and communication among Government, industry, and academia. Even within the same organization, it requires that technical and policy personnel communicate effectively, so that there is ample understanding of the new rules of the advanced materials game. While the technical challenges are many, the potential rewards are also great. The presentation of these technical constraints is the first key component of the Program Plan. They give us an idea of the direction of current and future research needs if we are to employ these new materials to their full potential. The next part of the report presents the materials research programs of various countries. Emphasis is given to the U.S. programs.

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PART IV

COMPARATIVE NATIONAL MATERIALS PROGRAMS FOR EUROPE, JAPAN, AND THE UNITED STATES

This part of the Program Plan examines the materials programs of key government agencies in Western Europe, Japan, and the United States. Emphasis is placed on U.S. Government agency programs in materials research. The U.S. Government has budgeted over $1 billion in materials research for fiscal year 1989. The research is concentrated in six agencies.

With the emergence of the global marketplace in the last several decades, comparative national policies have become important in understanding both the business climate within countries and the competitive status of individual companies. Government and industry policymakers can no longer view decisions solely in terms of a national agenda, but must anticipate the results of their actions on a global scale.

This part of the Program Plan examines the materials programs of key government agencies in Western Europe, Japan, and the United States. The second key component of the Program Plan, the presentation of the current largest U.S. agency materials programs, is included in this part.

Part IV of the Program Plan will set the stage for Part V, which presents a policy framework for understanding advanced materials issues, the final major component of the plan.

EUROPEAN MATERIALS PROGRAMS

Individual Country Programs

West Germany, France, and the United Kingdom have the largest advanced materials research and development (R&D) programs of Western Europe. The relative position of their programs depends on the specific materials involved. West Germany, for example, has the largest ceramics program, while France is the dominant country in advanced composites, especially polymer matrix. Sweden, Norway, Belgium, and Italy also have significant research programs in materials development.[1]

West Germany: The main government entity with concerns in the advanced materials area is the Ministry for Research and Technology. The ministry has recently launched a program that will spend $440 million in research over a 10-year period (1986 to 1995). The research concentrates on high-temperature metals, engineering polymers, powder metallurgy and ceramics. The West German ceramics program is the largest in Western Europe, and was estimated at about $75 million in 1985. Germany has about 10 percent of the European advanced composite market.

France: In recent years direct government support for advanced materials research has averaged about $150 million annually. In addition, the French government owns many of the companies which undertake advanced materials research. French research in advanced ceramics ($64 million in 1985) is carried out by several agencies. The bulk of the work is conducted at the National Center for Scientific Research. Other research funding comes through the Commission on Atomic Energy, Ministry of Defense, Ministry of Research and Technology, and the Ministry of Education, as well as others. France controls over half the European market in advanced composites. Large subsidies for French aerospace, automotive, and energy-producing companies make it hard to estimate the extent of government funding in the advanced composite areas. French companies, such as Pechiney, have been strong in metals and alloys for many years and are continuing to develop new systems, such as metal matrix composites.

United Kingdom: The government spends about $51 million annually for research into ceramics. The two major ceramics programs are Ceramic Applications for Reciprocating Engines and Advanced Ceramics for Turbines. These programs are jointly funded by

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[1] The source for the general description of the European programs and for the levels of spending is Office of Technology Assessment, "Advanced Materials by Design," June 1988.

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government and industry. Because of the United Kingdom's strong aerospace program, its Ministry of Defence sponsors most of the advanced composite research. The Department of Trade and Industry is the next largest source of government funding for advanced composite research. Organizations that conduct the research are the Atomic Energy Research Establishment, the Royal Aircraft Establishment, and the Experimental Aircraft Program.

Joint European Programs

It has been recognized by the European Community that there is a need among the member countries for coordination of technological research and development.

There are two main programs that involve advanced materials coordination within the European Community. Basic Research in Industrial Technologies for Europe (BRITE) has an emphasis on production technology. One of the largest BRITE materials programs is research on silicon carbide-reinforced titanium metal matrix composites. European Research in Advanced Materials addresses all of the major advanced materials including metals, ceramics, polymers, and composites.

The removal of all trade barriers within the European Community by 1992 could mean that they will be better able to compete on the world market and could offer a threat to U.S. and Japanese dominance in materials technologies and their end-use systems.

JAPANESE MATERIALS PROGRAMS

In Japan, planning and coordination of advanced materials research are largely the responsibility of the Science and Technology Agency within the Prime Minister's Office, with other significant activities within the Ministry for International Trade and Industry (MITI), the Ministry of Education, Science, and Culture, and the Defense Agency. Figure 4-1 shows the organizational structure that plans, coordinates, and funds Japanese efforts in fine ceramics (so-called because fine powders are the processed materials used to form high-performance ceramics). Similar structures exist for other high-technology areas in Japan.

The major responsibility for materials policy and research belongs to MITI, with policy guidance from the Prime Minister's Office through the Science and Technology Agency (STA), the Science Council of Japan, and the Science and Technology Council. The Agency for Industrial Science and Technology (AIST) manages the government Research Institutes and Laboratories and assumes a major role in formulation of science and technology policy.

MITI-AIST Projects

The Agency for Industrial Science and Technology operates 16 institutes, 9 of which are located at the Tsukuba Science City. Table 4-1 lists all the institutes and laboratories at Tsukuba, with the AIST institutes indicated by asterisks.

The AIST institutes are devoted to testing and research to upgrade Japanese standards in manufacturing technology with the stated goal of leadership in industrial research and development. Research projects are classified as basic (ongoing research), which includes more than 500 themes being pursued, or as special (goal-oriented research), with more than 100 themes in 18 major areas. Selected activities are as follows.

Research and Development Project of Basic Technologies for Future Industries: This project, initiated in 1981, is a 10-year effort to provide basic technical knowledge and manufacturing capabilities in 13 areas within 3 major categories. The largest single category is for new materials research. Table 4-2 gives the breakdown for the new materials and future electron devices categories. The other category is biotechnology.

In Japan most projects are funded by the government at about the 10-percent level, with the remaining 90 percent provided by industry. The Future Industries Project, however, is funded solely by AIST.

The Japanese approach to R&D is typified by the ceramics effort. A nongovernment group, the Engineering Research Association for High-Performance Ceramics, was established to conduct the work. It consists of 15 private

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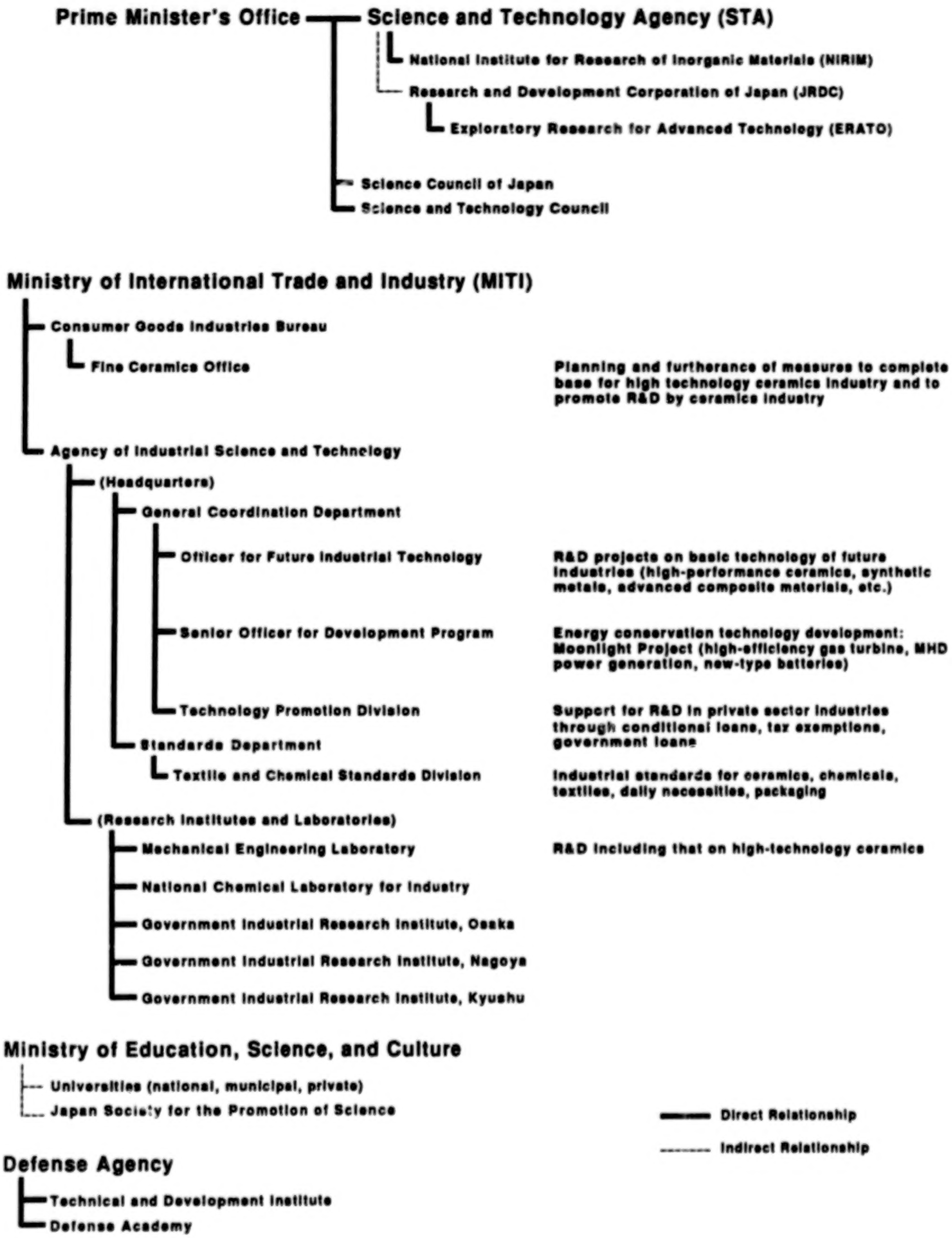
Figure 4-1. Japanese Government Involvement in Ceramics



- **Prime Minister's Office**
  - **Science and Technology Agency (STA)**
    - National Institute for Research of Inorganic Materials (NIRIM)
    - Research and Development Corporation of Japan (JRDC)
      - Exploratory Research for Advanced Technology (ERATO)
  - Science Council of Japan
  - Science and Technology Council
- **Ministry of International Trade and Industry (MITI)**
  - Consumer Goods Industries Bureau
    - Fine Ceramics Office — Planning and furtherance of measures to complete base for high technology ceramics industry and to promote R&D by ceramics industry
  - Agency of Industrial Science and Technology
    - (Headquarters)
      - General Coordination Department
        - Officer for Future Industrial Technology — R&D projects on basic technology of future industries (high-performance ceramics, synthetic metals, advanced composite materials, etc.)
        - Senior Officer for Development Program — Energy conservation technology development: Moonlight Project (high-efficiency gas turbine, MHD power generation, new-type batteries)
        - Technology Promotion Division — Support for R&D in private sector industries through conditional loans, tax exemptions, government loans
      - Standards Department
        - Textile and Chemical Standards Division — Industrial standards for ceramics, chemicals, textiles, daily necessities, packaging
    - (Research Institutes and Laboratories)
      - Mechanical Engineering Laboratory — R&D including that on high-technology ceramics
      - National Chemical Laboratory for Industry
      - Government Industrial Research Institute, Osaka
      - Government Industrial Research Institute, Nagoya
      - Government Industrial Research Institute, Kyushu
- **Ministry of Education, Science, and Culture**
  - Universities (national, municipal, private)
  - Japan Society for the Promotion of Science
- **Defense Agency**
  - Technical and Development Institute
  - Defense Academy

Source: High Technology Ceramics in Japan. National Research Council. 1984.

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Table 4-1. Tsukuba Science City

Higher Education and Training Group
- University of Tsukuba
- University of Library and Information Science
- National Laboratory for High Energy Physics
- Tsukuba Botanical Garden, National Science Museum
- National Education Center Annex
- Tsukuba International Centre JICA
- Tsukuba International Agricultural Training Centre JICA

Construction Group
- National Research Center for Disaster Prevention
- Tsukuba Telecommunication Construction Engineering Development Center, NTT
- Geographical Survey Institute
- Public Works Research Institute
- Building Research Institute

Science and Engineering Group
- National Research Institute for Metals, Tsukuba Laboratories
- National Institute for Research in Inorganic Materials
- Tsukuba Space Center, NASDA
- The National Institute for Environmental Studies
- Tsukuba Administration Office Agency of Industrial Science and Technology
- *National Research Laboratory of Metrology
- *Mechanical Engineering Laboratory
- *National Chemical Laboratory for Industry
- *Fermentation Research Institute
- *Research Institute for Polymers and Textiles
- *Geological Survey of Japan
- *The Electrotechnical Laboratory
- *Industrial Products Research Institute
- *National Research Institute for Pollution and Resources
- Meteorological Research Institute
- Aerological Observatory
- Meteorological Instruments Plant

Biological and Agriculture
- Tsukuba Primate Center for Medical Science National Institute of Health
- Tsukuba Medicinal Plant Research Station National Institute of Hygienic Science
- National Agriculture Research Center
- National Institute of Agrobiological Resources
- National Institute of Agro-Environmental Sciences
- National Institute of Animal Industry
- Fruit Tree Research Station
- National Research Institute of Agricultural Engineering
- Sericultural Experiment Station
- National Institute of Animal Health
- National Food Research Institute
- Tropical Agriculture Research Center
- Forestry and Forest Products Research Institute
- Tsukuba Office, Secretariat of Agriculture, Forestry, and Fisheries Research Council
- Tsukuba Seed Testing Laboratory, Ministry of Agriculture, Forestry and Fisheries
- Life Science Center. The Institute of Physical and Chemical Research

Common Facilities
- Tsukuba Center for Institutes
- The Japan Information Center of Science and Technology, Tsukuba Branch

Private Research Institutes
- The Japan Automobile Research Institute Inc.
- Institute of Ocean Environmental Technology Japan Foundation for Shipbuilding Advancement
- Testing Laboratory of Center for Better Living
- Central Research Institute for Feed and Livestock The National Federation of Agricultural Cooperative
- Nippon Agricultural Research Institute
- Foundation for Advancement of International Science

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*AIST Institutes

companies and four government laboratories. Each has been given a single assignment related to processing of materials and manufacturing methods. This effort is coordinated by an advisory committee based in the Ministry for International Trade and Industry (MITI). In each case the purpose of the project is to develop a manufacturing process for commercial products. The mix of industrial and governmental participants is chosen to address a menu of technical problems and provide an infrastructure for dialogue and transfer of information.

The Large-Scale Project: AIST promotes research and development on technological themes selected on the basis of importance and high priority for the heavy industries.

Table 4-2. Research and Development Project of Basic Technologies for Future Industries (Materials-Related Categories) (10-year funding from 1981 to 1990)

New Materials - 17,566,000,000 Yen ($130 million)[1]
- High-Performance Ceramics
- Synthetic Membranes for New Separation Technology
- Synthetic Metals
- High-Performance Plastics
- Controlled Microcrystalline Materials
- Advanced Composite Materials

Future Electron Devices - 7,857,000,000 Yen ($58 million)
- Superlattice Devices
- Three-Dimensional Integrated Circuits
- Biodevices

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[1] Dollar values are approximations based on 9/88 Yen values and are not necessarily directly comparable to U.S. domestic buying power.

Medical and Health Equipment Technology: Research, rapid development, and practical application of difficult-to-develop equipment with high technological risk is conducted and funded.

Projects of the Science and Technology Agency

As shown in Figure 4-1, the Science and Technology Agency plays a major role in research and policy in materials. Of six national laboratories under STA, the following have been the two largest and most successful:

The National Institute for Research in Inorganic Materials: This organization, located at Tsukuba Science City, was founded in 1966 to do research in ultrahigh purity, as well as quality materials for heat and corrosion resistance, superhard components, and electronics. Fifteen research groups, each with 6 to 10 members, conduct the research. The staff is augmented by 15 to 20 trainees from industry and 33 positions for visiting professors. Trainees' and professors' salaries are paid by their home companies or universities.

The National Research Institute for Metals: This organization is located in Tokyo but established laboratories and an administrative section at Tsukuba in 1979. Research is conducted by the High Strength Materials Division, Nuclear Materials Division, and the Superconducting and Cryogenic Materials Research Group. Like the National Institute for Research in Inorganic Materials, the National Research Institute for Metals concentrates on high-performance materials development, with emphasis on manufacturing.

Exploratory Research for Advanced Technology

The Exploratory Research for Advanced Technology program of STA, directed by the Research and Development Corporation of Japan, selects leaders from industry and universities for research programs to explore projects of potential value as future industries. Efforts are being made in ultrafine particles, amorphous and intercalated compounds, fine polymers, perfect crystals, bioholonics, and bioinformation transfer.

In regard to the capability of creating new and innovative technology, Japan is evidently still lagging behind, especially in the fields of technology which serve as the base for the establishment of future industries. These include space, aircraft, data processing, biotechnology, and new energy industries. Japan is said to be generally 5 to 10 years behind the United States and Europe in these areas.

In an attempt to respond to the above situation, MITI inaugurated the "Research and Development Project of Basic Technology for Future Industries" in fiscal year 1981. The project identifies revolutionary basic technologies essential to the establishment of the new industries expected to flourish in the 1990's.

MITI listed and prioritized the 10 most important technological innovations since 1973 and uses the list in establishing priorities in research and product development:

1. Large-scale integration
2. Biotechnology
3. Fiber optics
4. Industrial robots
5. Advanced ceramics
6. Interferon
7. Office automation
8. Other new materials
9. Supercomputers
10. Space technology

MITI and STA have served as planners, consensus-formers, and facilitators, with research funding by government used primarily as seed money, which represents usually about 10 percent of the total collaborative research budget.

UNITED STATES MATERIALS PROGRAMS

Individual Agency Programs

On March 29, 1988, a second Council workshop was sponsored by the Federation of Materials Societies in order to provide input to the Advanced Materials Program Plan. Formal presentations covering the overall scope of their materials efforts were given by the six agencies with the largest materials budgets. In addition, two agencies gave briefings during the roundtable discussion that followed. The results of that workshop serve as the basis for the following description of their programs. Additional information has been added where appropriate.[2]

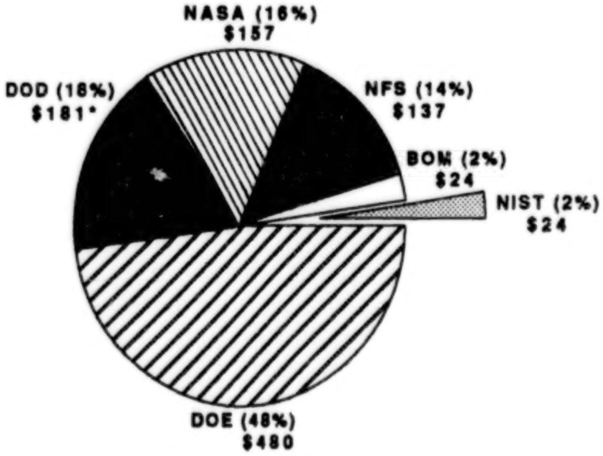
The U.S. Federal Government has budgeted more than $1 billion in fiscal year 1989 for materials research. As shown in Figure 4-2, the funds are concentrated in six agencies. The Department of Energy (DOE) spends about $480 million. The Department of Defense (DOD) spends approximately $181 million. The National Aeronautics and Space Administration (NASA) materials budget is about $157 million. The National Science Foundation (NSF) budget is about $137 million. The remaining funds are allocated to the Bureau of Mines (BOM) and the National Institute of Standards and Technology (NIST); each receives about $24 million.

Department of Energy: The Department of Energy undertakes research and development in materials in support of its missions related to energy development and nuclear weapons design, development, and production. As part of its overall materials research activities, it explicitly carries out basic research underpinning the Department's technology goals and develops instruments and major facilities which are available and used by researchers throughout the country. These major facilities include neutron sources and synchrotron radiation sources which can be used to determine the structure of and to characterize advanced materials.

These efforts, both basic and applied, form the scientific and technological base that DOE and U.S. industry need to carry out cost-effective

Figure 4-2. U.S. Government Materials Budget, Fiscal Year 1989

Percentage by Federal Agency and Dollar Amounts in Millions



*Includes generic research only.

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[2] The program descriptions and funding amounts are not all inclusive, but are illustrative of the overall effort.

commercialization programs and to remain competitive.

In addition to the basic work carried out in DOE's Office of Energy Research, the major technology groups of DOE are solar energy, fossil energy, nuclear energy, energy conservation, and defense programs. The important areas of materials research in support of the above technology areas include high-temperature superconducting materials, amorphous metallic alloys, strained layer superlattices for semiconductor applications, high-precision instrumentation, computer simulation techniques, x-ray lithography (semiconductor manufacturing), high-strength and high-temperature structural ceramic and metallic materials, solid electrolytes for batteries or fuel cells, corrosion-resistant solar-photothermal materials, high-hardness erosion- and corrosion-resistant materials, and new and emerging materials processing routes that permit the preparation of new or greatly improved materials.

In the Office of Conservation and Renewable Energy, materials research is under way in many programs, including energy utilization, buildings, industrial programs, transportation systems, energy storage and distribution, solar heat technologies, solar electric technologies, and renewable energy technologies. Some of the more significant efforts are concerned with developing structural ceramics for a variety of energy-related applications, recycling polymers, investigating high-temperature properties of ordered intermetallic compounds, processing semiconductors for photovoltaic applications, developing new electrolytes for batteries, developing processing techniques for high-temperature superconductors, and developing mirrors and concentrators for solar energy. In the Office of Nuclear Energy, materials research is under way in support of various programs, including high-temperature gas-cooled reactors, waste technology, uranium enrichment, liquid metal reactors, and space systems. The significant areas include development of graphite for reactor applications, structural materials for reactor environments, and improved high-temperature metals and glasses for encapsulation of irradiated materials. The Office of Civilian Radioactive Waste Management supports materials research aimed at developing packaging techniques for containing radioactive waste. In the Office of Defense Programs, materials research is under way to support the weapons research, development, testing, and waste treatment activities. The Office of Fossil Energy supports materials research that assists the development of technologies to convert coal to liquid and gaseous fuels, to increase domestic production of coal, oil and gas, and to ensure the efficient and environmentally compatible utilization of coal and other fossil energy resources. Research is under way on welding, hydrogen attack of pressure vessel steels, corrosion, and the development of ceramics.

In the basic research area, the Office of Basic Energy Sciences supports materials research covering a wide spectrum of activities aimed at understanding materials properties and phenomena of interest to DOE. It covers all materials classes including metals, alloys, ceramics, polymers, semiconductors, and superconductors. A major thrust in the program is to better understand the properties and behavior of the new high-temperature oxide superconductors. More emphasis is on the use of ultrahigh-brightness light sources and large-scale computational capability in the solution of materials sciences problems. Work is under way on non-equilibrium and artificially structured materials, interfacial phenomena, materials synthesis, materials reliability and life prediction, synthetic metals and new high-strength polymers, and magnetic materials, among other subjects. The basic research program also develops instruments and facilities used to characterize materials. Among the major materials research user facilities supported in the Basic Energy Sciences program are the High-Flux Beam Reactor, National Synchrotron Light Source, Intense Pulsed Neutron Source, Los Alamos Neutron Scattering Center, Stanford Synchrotron Radiation Laboratory, and the High-Flux Isotope Reactor.

The DOE Energy Materials Coordinating Committee compiles an annual technical report summarizing its many materials activities. The fiscal year 1989 budget is projected as $480 million.

Department of Defense: The Department of Defense is a major funding source for research and exploratory development of advanced materials and structures, with annual expenditures amounting to between $150 million and $300 million. The Department's efforts are executed at defense laboratories and other laboratories, universities, industry, and not-for-profit institutions. The effort is multidisciplinary in nature, involving physics, chemistry, ceramics, metallurgy, mechanics, and even biology. Attention is also directed to bulk specimens, films, interfaces, and surfaces, as well as both homogeneous and heterogeneous materials.

In the area of electronic and electrical materials, DOD is engaged in such research as higher speed and higher efficiency electronics, ultrasubmicron structures, elemental and compound semiconductors (including diamonds), superlattices and quantum wells, high electron mobility transistor structures, microwave and millimeter wave integrated circuit structures, conducting polymers, dielectrics, thermionic emitters, passivation, packaging, and superconducting sensors, electronics, and magnets.

In optical materials, DOD is focusing attention on glass, crystalline and plastic optical elements, as well as infrared windows, coatings, nonlinear materials for countermeasures, optical processor materials (for storage, modulation, switching, and amplifying), laser components, integrated electronic/optical materials, and low-loss optical fibers.

Efforts in sensor materials relate to needs in acoustics, chemical and biological defense, magnetism and electromagnetic waves (radio frequency, microwave, millimeter wave, infrared, visible, ultraviolet, x ray, and gamma ray). The structural materials under investigation include alloys, composites, polymers, adhesives, armor and light-weight, high-strength, high-modulus tough materials for aircraft, missiles, and spacecraft. Other areas of importance include propulsion and power materials such as rocket casings and nozzles.

Because producing very high quality, performance-driven materials systems is so important to the Department's mission, it is heavily involved in materials processing technology. Emphasis is placed on such approaches as mechanical/thermal/pressure, chemical, laser, electron beam, ion implantation, radiation, epitaxy (liquid, chemical vapor deposition, molecular beam), and joining (welding, compositing).

Some examples of the programs of the individual branches and agencies are as follows:

Army Programs: Within the Army, advanced materials provide enhancements in firepower, mobility, armament, communication, and personnel protection. To meet the anticipated future battlefield requirements in the year 2000, the Army will need the following:

1. More advanced materials possessing special combinations of properties. These include organic and inorganic materials exhibiting unique electromagnetic and strength properties, new classes of polymers which have toughness and environmental stability at elevated temperatures, and composites which have high stiffness, toughness, and strength-to-weight characteristics.

2. The means to achieve and retain, on a reproducible and reliable basis, important engineering properties in advanced materials in order to increase combat readiness and service life.

The total budget for Army materials research is about $19.9 million for fiscal year 1989.

Navy Programs: The fundamental research program of the Materials Division, Office of Naval Research, is a multidisciplinary effort involving materials (for example, metallurgy and ceramics) research as well as the solid-state aspects of physics and chemistry. The division's research is divided into the following three programs: Structural Materials, Materials Interfaces, and Functional Materials.

The Structural Materials Program emphasizes understanding the deformation and fracture processes in metals, intermetallics, ceramics, composites (ceramic, metal, and carbon), and solids with ultrafine microstructures. The Materials Interfaces Program emphasizes research on aqueous corrosion prevention (passivity, inhibition, and organic coatings), high-temperature corrosion prevention via coatings, adhesion mechanisms, tribological processes and surface-force phenomena. Studies tailoring the properties of composites through interface control are also part of the effort. The Functional Materials Program emphasizes research on acoustic damping mechanisms, piezoelectric and electrostrictive properties, electromagnetic energy-absorbing mechanisms, magnetic

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behavior, superconductivity, and new infrared-transmitting solids (diamond and composites). Processing-science research integrates the work of all three divisions. The total Navy materials budget for fiscal year 1989 is $25.1 million.

Air Force Programs: The directorate of chemical and atmospheric sciences of the Air Force Office of Scientific Research conducts research in many different areas. Chemical structures research includes work in solution ceramics, ultrastructure processing of ceramics, optical glass, nonlinear optical polymers, macromolecular ultrastructures (blends), ordered polymers, and molecular composites. Other programs include work in structural and electronic polymers, electronic materials surface chemistry, synthesis and chemical reactivity work in preceramic polymers, and biosynthesis of ceramics and polymers. The chemical computations branch does work on theory in support of nonlinear optical polymers, polymer blends, sol-gel processing, and energetic materials. The polymer branch works with molecular composites and nonlinear optical polymers, doing about half the research in-house and half with universities. The directorate of electronic and material sciences research programs include participation in the joint services electronics program, physical electronics (including wafer level union and magnetic materials initiatives), antennas and propagation, optical signal processing, high-frequency superconductive electronics, signal processing and artificial intelligence, metallic materials, nonmetallic materials, and manufacturing sciences (including nondestructive evaluation). The total Air Force materials budget for fiscal year 1989 is $86.3 million.

DARPA Programs: The Defense Advanced Research Projects Agency, Defense Sciences Office, Materials Science Division, conducts work in various areas. Metals research includes metal matrix composites, intermetallic compounds, intelligent materials processing and high-temperature structural composites (University Research Initiative). Ceramics work includes synthesis and processing of advanced ceramics and ceramic composites, high-temperature ceramic superconductors, and fiber coatings. Polymer work includes high-temperature polymers, structural and conducting polymers (University Research Initiative), electrochemical power sources, and energetic materials. Other areas include radar-absorbing materials and structures, carbon-carbon composites, eye and sensor protection, computational mechanics, applied and computational mathematics, turbulent flow in fluid dynamic systems (University Research Initiative) and neural networks. The Defense Advanced Research Projects Agency has also instituted a new Defense Manufacturing Office. The agency's total materials research budget for fiscal year 1989 is $50 million.

The combined total DOD budget for generic materials research for fiscal year 1989 is about $181 million.

National Aeronautics and Space Administration: Three prominent areas of advanced materials technology under development within the National Aeronautics and Space Administration are high-temperature materials, light alloys, and organic composites. Emphasis on high-temperature materials is focused on continuous-reinforced composite materials, specifically metal matrix, intermetallic matrix, ceramic matrix, and carbon-carbon composites. Service temperature goals for these materials are up to 2,000°F for airframes and 3,000°F and higher for engines. Light-alloys for airframe and launch vehicles must be able to withstand a temperature range from cryogenic to elevated (1,600°F) temperatures. Both monolithic and composite materials are examined in this category. Much emphasis is placed on aluminum alloys, but titanium and intermetallics are also examined. Beginning fiscal year 1989, NASA will undertake a new initiative to introduce advanced composite technology into airframe design. The goal is that within 5 years, revolutionary composite technology will be introduced into airframe construction.

An important policy concern to NASA is the length of time from conception to application for a new materials system. The current period of at least 10 years, and usually more, could be reduced with better coordination between government and industry.

In addition, most NASA activities result in some type of technology transfer. NASA operates a variety of space and terrestrial experimental and flight facilities. The goal is to advance scientific and technical understanding for the direct benefit of the aerospace and scientific community. NASA supports this constituency by funding programs to explore the universe, develop advanced communications satellites, improve satellite imaging sensors, and so forth. This direct technology transfer is universally accepted as inextricably tied to NASA's mission.

During the past 25 years, NASA's technology transfer program has resulted in an estimated 30,000 secondary applications, or "spinoffs." These have been of benefit to a wide variety of users throughout the United States in the fields of medicine, transportation, resource management, energy, public safety, manufacturing technology/industrial productivity, and consumer goods. For example, digital image processing, developed to enhance pictures of the moon, is now used to enhance imagery in medical diagnostic techniques such as CAT scans and nuclear magnetic resonance, quality control systems in industrial plants, cartography, manufacture of printed circuitry, metallurgy, ultrasonics, and seismography.

NASTRAN, NASA Structural Analysis Computer Software, is an extremely complex and sophisticated computer program designed to analyze the structural components of aircraft and space vehicles. NASTRAN permits designers and engineers to analyze and solve thousands of structural problems in a matter of hours rather than the months required when using conventional mathematical methods. It has been used by hundreds of industrial firms to solve structural problems in automotive, aircraft, chemical plant, oil refinery, rail vehicle, and architectural design. Aerospace requirements for superefficient, ultrareliable, small, lightweight components have spawned a line of implantable medical devices. These devices utilize such space technologies as advanced long-life batteries, microminiaturized units, and electronic sensors and telemetry which regulate heart rhythms, automatically inject medication to targeted organs of the body, and monitor internal body temperature.

NASA's materials research budget for fiscal year 1989 is about $157 million.

The National Science Foundation: The National Science Foundation provides support to scientists and engineers at academic institutions to create new knowledge, which is deemed essential for technological innovation, and to train personnel to enable the United States to play a leading role in the knowledge-based global economy.

Much of NSF's current work is in response to evidence suggesting that the United States may not have an adequate pool of scientific and engineering talent to meet this challenge. The U.S. college-age population is decreasing in size and fewer U.S. students are opting for a career in science or engineering. At the same time, there has been an alarming increase in the proportion of non-U.S. students earning doctoral degrees in various fields of mathematical, physical, and materials science and engineering during the past two decades. In order to address these problems, NSF provides support for the training of under-represented groups (women and minorities) for careers in technical fields.

Support for materials research is available from several sources at NSF, although its major concentration is from the Division of Materials Research (DMR) (approximately $116 million in fiscal year 1989). The division's goals include advancing fundamental understanding of the physics and chemistry of materials and processes; determining the complex interrelationships between structure, properties, processing, and performance of materials at all dimensions (nanoscale through large-scale structure and systems); training scientists and engineers; and facilitating the transfer of knowledge to the national technology base.

DMR supports theoretical and experimental materials research using a variety of funding modes. It provides support for individual investigators doing disciplinary research, for materials research laboratories engaged in broadly based interdisciplinary and multidisciplinary research, for materials research groups tackling complex problems requiring a team approach, for large-scale national facilities, and for instrumentation development and acquisition. DMR is also involved in co-support of joint or NSF-wide initiatives, such as computational science and engineering, materials chemistry, materials processing, and high-temperature superconductivity research. Processing of high-performance ceramics, ion implantation of dilute semiconductors, cationic polymerization, biomaterials, electro-optical materials, and high-temperature superconductivity are all examples of how long-term support for fundamental materials research has resulted in advancements of knowledge that can improve both the quality of life and, ultimately, U.S. competitiveness. The NSF materials research budget for fiscal year 1989 is about $137 million, based on the Engineering Directorate and the DMR budgets.

Department of Commerce, National Institute of Standards and Technology: Materials research in the National Institute of Standards and Technology, which was formerly known as the National Bureau of Standards, is distributed throughout the organization, although its major concentration is in the Institute for Materials Science and Engineering (IMSE). The focus for IMSE is increasingly on ceramics, polymer blends, metals with radically altered internal structures and properties, and composites (polymer, metal, ceramic). Other materials-related programs include advanced measurement technologies, high-temperature superconductivity, high-performance composites, intelligent processing, and basic science. The NIST research reactor is involved in developing a national user facility for cold neutron research, which will provide 15 unique research facilities, that will commence use in 1990.

In all programs of NIST there is direct involvement of industrial participants. The mission of NIST is to serve industry in areas of standards and technology development. Industry, therefore, has a role during all project phases from early planning through final implementation. Through the industrial research associate program, scientists and engineers from industry (on industry payroll) work on location with NIST scientists on programs that they have jointly conceived.

The broad mission goals of NIST allow it to focus on science development and technology transfer in materials-related research. Congress has recognized this and has given NIST new responsibilities in materials coordination and technical direction (contained in the same legislation that changed its name).

The Institute for Materials Science and Engineering has data programs in phase diagrams, crystal data, tribology, and corrosion data. All these programs are carried out in collaboration with industry and professional organizations; for example, the corrosion data program is carried out in conjunction with the National Association of Corrosion Engineers and the Materials Technology Institute. NIST is involved with the design and implementation of an expert system to serve the material information needs of those working with corrosion problems associated with hazardous chemicals. The first project involves corrosion problems associated with concentrated sulfuric acid. Such systems are a way to leverage the knowledge of a materials or corrosion expert within a given organization. The NIST materials budget for fiscal year 1989 is about $24 million.

Department of the Interior, Bureau of Mines: BOM has significantly expanded its role with traditional materials to begin considering the impact of advanced materials on the traditional commodity materials. The Bureau's efforts relating to advanced materials are under way in both its Research Directorate and its Information and Analysis Directorate.

The new Office of Advanced Materials Coordination, within the Bureau, is charged with maintaining technical awareness, identifying and monitoring the advanced materials industry, developing new data acquisition methods, projecting materials use patterns, fostering interagency cooperation, and providing input to the National Critical Materials Council as well as other Federal bodies. In addition to the publication of a series of new analytical studies on advanced materials, another major effort under way is the compilation of a data base to include advanced materials companies, products, production volumes, end uses, and company ownership.

The Bureau's research into advanced materials is placing increased emphasis on wear-resistant materials, materials synthesis and joining, remote sensing, robotics, nondestructive evaluation, and substitutes for strategic and critical minerals. The BOM materials research budget for fiscal year 1989 is about $24 million.

Materials Coordinating Bodies

There are several important mechanisms in place to help coordinate U.S. national materials programs. The Federal Coordinating Council for Science, Engineering, and Technology's

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(FCCSET) Committee on Materials (COMAT) is responsible for providing interagency coordination in materials-related topics. It also identifies issues of importance and makes recommendations regarding these issues to the Science Advisor to the President. FCCSET is under the Office of Science and Technology Policy in the Executive Office of the President. COMAT includes representatives from virtually all agencies which have any direct responsibility or interest in materials-related issues or programs (the Departments of Commerce, Defense, Energy, Interior, Transportation, Treasury, and Agriculture; Federal Emergency Management Agency; NASA; National Institutes of Health; Nuclear Regulatory Commission; National Science Foundation; Office of Management and Budget; and United States Trade Representative). It has established seven active subcommittees to provide a focus on currently important segments of this field: superconducting materials, interagency materials group, ceramic materials, composite materials, intelligent materials processing, nondestructive evaluation of materials, and the Versailles Project on Advanced Materials and Standards.

COMAT issues reports on various topics as appropriate. For example, in 1988 it produced a report describing the Federal programs in superconductivity, in view of the current significance of this technological topic. In 1988, COMAT, along with other FCCSET committees, was assigned the responsibility to identify and have its chairman discuss, with designated coordinators from Japan, areas for possible cooperation under the recent U.S.-Japan Science and Technology Agreement signed by President Reagan and Prime Minister Takeshita on June 20, 1988. Specifically, COMAT will evaluate the topics of advanced materials (including superconducting materials, manufacturing technology, process controls, and automation) and will co-evaluate, with the FCCSET Committee on Computing, the topic of data bases. Through its inherent interagency coordination mechanisms, it will establish new government programs of cooperation in the spirit of the U.S.-Japan Agreement and monitor their progress under the guidance of the Joint High-Level Committee which oversees this agreement. The Chairman of COMAT serves as a member of the Joint Working Level Committee that supports and recommends programs to the Joint High Level Committee. COMAT has worked with the Council in cosponsoring the workshops to obtain information for this Program Plan. It has also provided select material for the plan itself.

There are additional mechanisms including the Interagency Materials Group, which is hosted by the NSF, as well as agency-specific coordinating mechanisms, such as DOE's Energy and Materials Coordinating Committee. There are also materials specific groups such as the Interagency Coordinating Committee for Structural Ceramics.

In addition, the National Critical Materials Council is involved in advanced materials R&D coordination with the various agencies involved in carrying out research and among the Federal Government, industry, and academia.

U.S. Congressional Materials Responsibility

The U.S. Congress has mineral, materials, and research responsibilities decentralized among several committees and subcommittees. On the House side, the Committee on Science, Space, and Technology has several subcommittees which have responsibilities in the materials and minerals areas. The Subcommittee on Transportation, Aviation, and Materials has the lead role in materials research and development and national material policies. Other subcommittees which have responsibility in related areas include Energy Research and Development, through oversight of nonmilitary energy laboratories; and Science Research and Technology, through oversight of technology transfer and R&D policy. Under the Committee on Interior and Insular Affairs, the Subcommittee on Mining and Natural Resources has responsibilities which center on conventional commodity minerals and materials. In addition, the House Committee on Armed Services contains a Subcommittee on Seapower and Strategic and Critical Materials which over the years has played an important role in materials policy planning.

On the Senate side, the Committee on Armed Services has a Subcommittee on Defense Industry and Technology. The Committee on Commerce, Science, and Transportation has a subcommittee on Science, Technology, and Space. The Committee on Energy and Natural Resources contains a Subcommittee on Mineral Resources Development and Production.

In addition, other committees and subcommittees, such as Appropriations and Budget in both the House and Senate, will from time to time have reason to become involved in mineral or materials technology issues.

SUMMARY

Part IV has presented a brief picture of the international arena of national materials programs. Valid comparisons across countries are always difficult. We have emphasized the programs of the largest U.S. Government agencies engaged in materials research. The presentation of these programs is the second major component of the Program Plan.

In the next part, we examine the U.S. policy climate in more detail in order to establish the factors identified as influencing advanced materials development and commercialization. Those factors are then linked to recent legislation and executive initiatives and policies. This policy framework is the third and final major component of the Program Plan.

PART V

ADVANCED MATERIALS ISSUES AND POLICY FRAMEWORK

Nine policy areas have been identified as being important to advanced materials research, development, and commercialization. These policy areas are: coordination and communication within Government; coordination and communication among Government, industry, and academia; antitrust laws; intellectual property rights; product liability and tort law; education; Government's role in research funding; regulatory policies; and international issues.

In this part we examine how the climate created by U.S. Government policy affects research, development, and the eventual commercialization of new materials. We discuss how the Administration has addressed key issues of importance to the advanced materials industry. We note in passing that many of the issues identified in the National Critical Materials Council's (NCMC) communications with industry representatives are not specific to materials, but are generic to all science and technology research enterprises.

The Council has relied on many sources of information in the public and private sectors. Two of the most important sources of information were roundtables held on January 6 and March 29 of 1988. The first roundtable provided an opportunity for industry and academic leaders to provide suggestions for the direction of the Advanced Materials Program Plan. Those suggestions tended to be policy rather than technically oriented. That first roundtable was the primary source for many of the issues identified below. The results of the second roundtable were used in the previous part of this report to describe the materials programs of various government agencies.

Other sources of information are the many studies that have been conducted by government and by independent organizations. An additional source for policy suggestions has been the less formal input from a wide range of leaders in the public and private sectors. They have communicated with the Council and staff through letters, informal meetings, and telephone conversations. The concerns identified through these sources form the policy framework discussed here.

Some of the issues can be appropriately addressed by government policy, while others are either beyond the purview of government policy, or appear to the Reagan Administration to be an inappropriate direction for government policy.

To better understand the materials policy of the Administration, it is necessary to examine its first comprehensive materials policy statement. This materials policy framework was first outlined in the President's National Materials and Minerals Program Plan and Report to Congress of April 5, 1982.

OVERVIEW: THE ROLE OF GOVERNMENT— A FRAMEWORK FOR DISCUSSION

In his April 5, 1982, National Materials and Minerals Program Plan and Report to Congress, the President stated:

> Since business enterprise is the primary engine of technological change, the driving force behind technological innovation through research and development is the expectation of a satisfactory return on invested capital. If there are circumstances, either real or perceived, which increase cost, increase the time to commercialization, increase risk or otherwise reduce the return on investment, innovation will be discouraged. Thus the first, and perhaps most important requirement for materials research and development is the existence of a favorable business and political climate which encourages both the initiation of the innovative process (financing research and development activities) and the undertaking of steps leading to commercialization (applied research and development).
>
> A critical element of materials research and development activities, and an area of traditional government support, is the basic research necessary to the development of a scientific data base. This requires close coordination between agency programs addressing supply problems and those addressing materials manufacture and performance.
>
> In addition, government intervention in and assistance of, technological development is appropriate

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> only where market forces are incapable of achieving clearly defined national objectives. Thus government's attention regarding research and development activity should focus on long-term, high-risk potentially high-payoff technology that has the best chance for wide generic application.

The Council believes that the principles outlined in the President's 1982 National Materials and Minerals Program Plan remain valid today. That is, market mechanisms achieve the most efficient allocation of resources within the economy and are fundamental to sound research and development (R&D) in this country. Indeed, government attempts to pick "winners and losers" inevitably fail. Therefore, efforts to have government direct or "steer" research towards specific products or technologies are more likely to hinder than to advance progress.

Further, any policy framework or plan regarding advanced materials research and development must have as its foundation reliance on the market to allocate efficiently the scarce technical and financial resources available for R&D from among competing national priorities. Also, R&D issues should be considered within a broad context rather than on an individual basis. Without the proper economic climate, R&D investment will be adversely affected. As a result, public policy questions that concern advanced materials are largely generic issues common to other areas of advanced research.

In its report, "Advanced Materials By Design," the Congressional Office of Technology Assessment, stated:

> In many respects, the competitive challenges facing advanced materials companies are a microcosm of the challenges facing the U.S. manufacturing sector as a whole. Therefore, advanced materials policy cannot be discussed in a vacuum.

It also noted:

> Advanced materials policies therefore, can most effectively be treated as one facet of a high-level, high-priority policy of strengthening the Nation's entire industrial and manufacturing base.

This view was reinforced further by the private sector workshop. During the workshop, participants cited broad, generic issues, such as product liability and the protection of intellectual property rights, as central concerns. The Administration has followed the course of addressing advanced materials policy within the broad context of its overall economic, national security, and R&D policy.

ISSUES OF IMPORTANCE TO ADVANCED MATERIALS RESEARCH, DEVELOPMENT, AND COMMERCIALIZATION—RESULTS OF THE PRIVATE SECTOR ROUNDTABLE

One of the key elements of the Program Plan developed by NCMC is the information obtained from the private sector regarding constraints on advanced materials research, development, and commercialization. On January 6, 1988, a workshop was co-sponsored by the Federation of Materials Societies, the Committee on Materials, and the Bureau of Mines to provide a forum through which leaders in industry and academia could make suggestions for the Advanced Materials Program Plan that NCMC would develop.

Council Chairman Hodel gave the keynote address and invited the guests to provide their views to the Council. The roundtable was broken into four workshop sections: ceramics, polymers, metals, and electronic materials. Each workshop section provided recommendations specific to its topic area, as well as generic comments that pertained more generally to both advanced materials and technical research.

Ceramics

The major concern of the participants was that man-made, high-purity materials for the manufacture of ceramic finished products were not, for the most part, available in the United States but had to be imported. The strongest competitors in the field are Japan, followed by the United Kingdom and West Germany. These advanced, or "fine," ceramics, as they are called by the Japanese, have important current and potential uses in defense, electronics, and heat engines. The attendees saw problems with these materials in the move from the basic research stage to final product form. Also, they saw the need to separate advanced ceramics and ceramic composites from other conventional ceramic materials (for example, plumbing fixtures) in the Standard Industrial Classification Codes.

Polymers

There were three factors identified by workshop participants as possibly restricting growth of the polymer industry in the United States: in defense contracts, lack of government recognition of fundamental differences between development of materials versus weapons systems; restriction of technology discussions outside the United States and its impact on our allies; and slowness of technology transfer from government to the private sector. There were three suggestions from this workshop: consideration of the problems of developing a national materials policy when industries are transnational, as is true for the polymer composites industry; multiyear funding for Federal R&D budgets to help maintain a stable research environment; and examination of the problem of product liability as it relates to polymers.

Metals

Issues that emerged during this workshop discussion were as follows: differing interpretations of antitrust laws by government and corporate attorneys leading to a reluctance on the part of many corporate counsels to allow involvement in cooperative R&D agreements; inadequate protection of intellectual property rights for corporate teams performing government contract R&D; and ceilings on independent recoverable R&D costs and other policies related to defense work that affect the earnings potential of defense contractors. Issues that participants identified for further consideration included clarification of the antitrust exemptions for cooperative R&D agreements, recommendations for improved protection of intellectual property rights under government R&D contracts, and development of a leadership role for the national laboratories in developing and disseminating a comprehensive body of design and specification literature for advanced materials.

Electronic Materials

The workshop discussion emphasized manufacturing and processing issues, specifically, that production and processing capabilities have a large impact on device and circuit performance. A significant amount of industrial resources are being consumed by intercorporation redundancy in the development of materials synthesis and processing technology. Participants also stated the belief that foreign competitors have targeted electronic materials as a key market for industrial competitiveness. The electronics section identified two areas for consideration: fostering greater coordination among various funding agencies, including establishment of procedures for financial tracking of electronics materials programs; and examining the proportion of government funding that is directed toward device, circuit, and system development. This proportion should be compared to materials and materials processing in light of the impact of the control of materials properties and processing on the effectiveness of devices and systems.

Through the workshops, informal exchanges, and reviews of related studies, at least nine key areas of concern, which are pertinent to the Council's mandate in regard to advanced materials research, development, and commercialization, have been identified. They are:

I. Coordination and communication within Government

II. Coordination and communication among Government, industry, and academia

III. Antitrust laws

IV. Intellectual property rights

V. Product liability and tort law

VI. Education

VII. Government's role in research funding

VIII. Regulatory policies

IX. International issues

The following discusses how these are currently being addressed as part of the development of the Council's Program Plan.

REAGAN ADMINISTRATION MATERIALS POLICY INITIATIVES

In his 1982 National Materials and Minerals Program Plan and Report to Congress, the President articulated specific policies to address many of the generic issues that affect advanced materials research. In implementing these and other policy initiatives, the Administration has made significant strides in addressing many of the issues important to fostering the proper environment for advanced materials research and development.

Issue I: Coordination and Communication Within Government

Background: Clearly, among the first tasks government should undertake is to assure that its own programs are appropriately coordinated and that agencies are aware of each other's activities. This function is carried out by the National Critical Materials Council and through several existing interagency committees. Among the most active of these are the Committee on Materials (COMAT), the Interagency Materials Group, and the Interagency Coordinating Committee for Structural Ceramics.

The Committee on Materials: The Federal Coordinating Council for Science, Engineering, and Technology's (FCCSET) Committee on Materials is responsible for providing interagency coordination in materials R&D-related topics. It also identifies issues of importance and makes recommendations regarding these issues to the Science Advisor to the President. FCCSET is under the Office of Science and Technology Policy in the Executive Office of the President. COMAT includes representatives from virtually all agencies which have any direct responsibility or interest in materials-related issues or programs (the Departments of Commerce, Defense, Energy, Interior, Transportation, Treasury, and Agriculture; Federal Emergency Management Agency; National Aeronautics and Space Administration; National Critical Materials Council; National Institutes of Health; Nuclear Regulatory Commission; National Science Foundation; Office of Management and Budget; and United States Trade Representative). It has established seven active subcommittees to provide a focus on currently important segments of this field: superconducting materials, interagency materials group, ceramic materials, composite materials, intelligent materials processing, nondestructive evaluation of materials, and the Versailles Project on Advanced Materials and Standards. COMAT issues reports on various topics as appropriate. For example, in 1988, it produced a report describing the Federal programs in superconductivity, in view of the current significance of this technological topic. COMAT has worked with the Council in cosponsoring the workshops discussed above and held with the primary purpose of obtaining information for this Program Plan. COMAT has also provided select material for the plan itself.

The Interagency Materials Group: This group is hosted by the National Science Foundation and works in close communication with COMAT. Its members include materials specialists, and it serves to strengthen further communications regarding materials-related research within the Federal Government.

The Interagency Coordinating Committee for Structural Ceramics: This committee is more focused than the other two principal materials-related committees and serves to coordinate policy regarding structural ceramics—a major area of materials research.

The National Critical Materials Council: The purpose of the National Critical Materials Council is to help coordinate materials policy both among the various agencies involved in carrying out R&D and among the Government, industry, and academia. The development of this plan is pursuant to that mandate.

Administration Actions Regarding Issue I

National Materials and Minerals Program Plan and Report to Congress, April 1982: The Administration recognized the value of utilizing existing structures for coordination of Federal materials policy in the 1982 materials plan, and as a result, established a set of goals through which needed intragovernmental coordination of minerals and materials policy could take place. The report stated in part.

> The Administration reaffirms the Committee on Materials (COMAT), under the direction of the Federal Coordinating Council on Science, Engineering, and Technology (FCCSET) for the coordination of Federal

> materials and minerals research and development activities, directing:
>
> 1. Assistant Secretary-level representation from the departments and agencies concerned with minerals and materials;
>
> 2. Placement within COMAT of the Department of Defense Material Availability Steering Committee and Interagency Materials Group;
>
> 3. Establishment of a Working Panel within COMAT to coordinate Federal research and development on essential materials;
>
> 4. Establishment of a formal mechanism within COMAT for information exchange between agency materials research and development program managers. . . .

The Administration has made substantial progress in implementing its goals in regard to COMAT and the coordination of Federal materials research. COMAT is particularly well suited to this task, because its makeup (that is, representatives of the various agencies conducting materials-related research) permits it to consider broad materials issues within a context of the specific missions of the individual agencies. Therefore, COMAT can strike a balance between broad national objectives and specific departmental requirements as they relate to advanced materials policies.

Importantly, COMAT falls under the authority of the President's Science Advisor, the official charged with overseeing broad issues in research and development within the Federal Government. This serves to assure further that these issues will be considered within the broadest possible context and with the highest possible visibility within the Executive Office of the President.

Issue II: Coordination and Communication Among Government, Industry, and Academia

Background: There are opportunities for enhanced coordination and communication between the private sector and the Federal research establishment. The Administration has pursued these opportunities, where appropriate, through a number of concrete actions.

One of the most important issues in the area of coordination and communication between the public and private sectors is the transfer of technology. Of the most widely known examples of products that have resulted from technology transfer, many are found in the space program, and include such products as the adhesive used to attach nonstick coatings to cookware, and the medical monitors used in hospital intensive-care units. Other examples of federally developed technologies include computers and radar.

Administration Actions Regarding Issue II

The Superconductivity Initiative and Federal Conference on Commercial Applications of Superconductivity: The discovery of superconductivity at higher temperatures—roughly equivalent to those required to liquefy nitrogen (77°K)—in January 1987 has great significance. Such a breakthrough could make possible applications of superconductivity not previously imagined.

The Administration responded to this profound scientific discovery by calling a Federal Conference on Commercial Applications of Superconductivity, in July 1987, at the same time issuing the President's Superconductivity Initiative.

The Conference on the Commercial Applications of Superconductivity brought together some 1,400 individuals from government, industry, and the academic community who had a direct interest in U.S. competitiveness. In his remarks to the gathering, the President described its purpose:

> We are here at this conference, so that business and science can cross-fertilize, can begin at these early stages to dream and plan together—because this new age of superconductivity is a new arena for the spirit of enterprise.

The conference alerted the Nation's scientists, engineers, and entrepreneurs to the opportunity at hand, and to the commitment of the Administration to exploit, through appropriate Federal R&D funding, the potential of superconductivity.

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The Superconductivity Initiative, issued in July of 1987 in conjunction with this conference, was formulated around three principal objectives:

1. To promote greater cooperation among the Federal Government, academia, and U.S. industry in the basic and enabling research that is necessary to continue scientific breakthroughs in superconductivity.
2. To enable the U.S. private sector to more rapidly convert scientific advances into new and improved products and processes.
3. To better protect the intellectual property rights of scientists, engineers, and businessmen working in the area of superconductivity.

To implement the initiative, three broad areas were addressed:

1. An increase in funds for basic research.
2. The removal of impediments to procompetitive collaboration on generic research and production.
3. The creation of mechanisms for the swift transfer of technology and technical information from the Federal Government to the private sector.

The proposals in this initiative can be divided largely into two categories: legislative proposals and administrative proposals. The legislative proposals included the following:

1. Amend the National Cooperative Research Act to include some types of joint production ventures.
2. Authorize Federal agencies to withhold from indiscriminate release information of commercial value that could harm U.S. economic competitiveness.

The administrative proposals included:

1. Establish a "Wise Men" advisory group on superconductivity.
2. Establish a number of superconductivity research centers.
3. Use all Federal agencies to implement quickly the steps outlined in Executive Order 12591 related to effective federally oriented technology transfer.
4. Direct the National Bureau of Standards (now called the National Institute of Standards and Technology) to accelerate efforts to develop and coordinate common standards for superconductors and related devices.
5. Reallocate funds towards superconductivity basic research.
6. Request that the Department of Defense accelerate work in superconducting magnet-based military applications.
7. Seek reciprocal U.S. opportunities to participate in Japanese government-supported research and development.

Considerable progress has been made towards achieving the goals set forth in the President's Superconductivity Initiative. Examples of concrete actions taken include the following:

1. The Superconducting Materials Subcommittee of COMAT was established. Its first meeting was in May 1987. Its purpose is to coordinate superconducting materials research. Relevant issues and concerns are identified and brought to the attention of COMAT. A comprehensive compilation of Federal research programs in superconductivity was produced by this subcommittee in May of 1988.
2. Redirecting research funds to superconductivity has resulted in outlays for high-temperature superconductivity rising from \$44.9 million in fiscal year 1987 to \$94.8 million in fiscal year 1988, and to an estimated \$135 million in fiscal year 1989.
3. The Superconductivity Advisory Group has been established with Dr. Ralph E. Gomory of IBM as its Chairman, and

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Dr. Praveen Chaudhari of IBM as its Executive Secretary. Its other members include Dr. Kent Bowen of the Massachusetts Institute of Technology, Dr. John Foster of TRW, Dr. Theodore Geballe of Stanford University, Mr. Kenneth Oshman, a private investor, and Dr. Robert Schrieffer of the University of California, Santa Barbara.

4. The Administration sent to Congress the Superconductivity Competitiveness Act of 1988 which includes the legislative changes outlined in the President's Superconductivity Initiative (previously described).

The Federal Technology Transfer Act of 1986: In 1986, with the support of the Administration, Congress enacted the Federal Technology Transfer Act of 1986 (Public Law 99-502). The act was established to aid the transfer of technology from Federal laboratories to the private sector. This legislation encourages directors of Federal labs to enter into cooperative research and development agreements with the private sector, universities, and State and local governments.

Authority is specifically given to the laboratory directors to negotiate licensing agreements and contracts. Special considerations are given to companies which intend to manufacture their products in the United States and to small businesses. In addition, cash awards are to be provided as incentives for individuals who make outstanding efforts and contributions in the area of science and technology transfer.

The Competitiveness Initiative and Executive Order 12591: The President recognized the importance of technology transfer in his 43-point January 1987 Competitiveness Initiative. One of the important provisions was an Executive order aimed at improving the transfer of technology from the Government to the private sector. On April 10, 1987, the President issued Executive Order 12591, "Facilitating Access to Science and Technology." In his statement accompanying the Executive order, the President said:

> I believe a vigorous science and technology enterprise involving the private sector is essential to our economic and national security as we approach the 21st century. Accordingly, I have today issued an Executive Order, "Facilitating Access to Science and Technology."
>
> It is important not only to ensure that we maintain American preeminence in generating new knowledge and know-how in advanced technologies but also that we encourage the swiftest possible transfer of federally developed science and technology to the private sector. All of the provisions of this Executive order are designed to keep the United States on the leading edge of international competition.

In implementing the Federal Technology Transfer Act of 1986 (Public Law 99-502), Executive Order 12591 serves a broad purpose described as ensuring that:

> Federal agencies and laboratories assist universities and the private sector in broadening our technology base by moving new knowledge from the research laboratory into the development of new products and processes.

To achieve this goal, it outlines a series of steps designed to:

> promote cooperation among the Federal Government, State, and local governments, industry and academia in cooperative research and the commercialization of research.

Included among the steps are these:

1. Directing Federal agencies to improve the transfer of federally developed technology and technical information. This transfer of knowledge to the marketplace is accomplished through various methods: first, by encouraging Federal laboratories to collaborate with State and local governments, universities, and business, particularly small business, through cooperative research agreements; and second, by encouraging "science entrepreneurs" to act as conduits among Federal laboratories, universities, and private industry.

2. Directing the Secretaries of Agriculture, Commerce, Energy, and Health and Human Services, and the Administrator of the National Aeronautics and Space Administration to select one or more of their laboratories to participate in the "Technology Share Program" involving multiyear joint basic and applied research with consortia of U.S. firms and universities.

3. Directing the President's Commission on Executive Exchange to assist Federal agencies in developing and implementing an exchange program whereby scientists and engineers in the private sector may take temporary assignments in Federal laboratories, and scientists and engineers in Federal laboratories may take temporary assignments in the private sector.

4. Issuing a number of directives aimed at facilitating access to new knowledge developed abroad.

    a. Federal agencies should consult with the United States Trade Representative when entering into cooperative R&D agreements, or licensing arrangements, with foreign agents. This consultation is to determine whether the country offers comparable research and development licensing opportunities for U.S. nationals and companies and protects U.S. property rights.

    b. The Secretary of State should develop a recruitment policy encouraging scientists and engineers from the Federal Government, academia, and industry to serve in U.S. embassy assignments abroad.

    c. The Secretaries of State and Commerce and the Director of the National Science Foundation should develop a central mechanism for the dissemination of science and technology information developed abroad. This information is then to be made available to users in Federal laboratories, academic institutions, and the private sector on a fee-for-service basis.

5. Directing the Secretary of Defense to identify within 6 months a list of funded technologies that would be potentially useful to U.S. industries and universities and to then accelerate efforts to make these technologies more readily available.

6. Directing Federal agencies to examine the potential for establishing university-based research centers in engineering, science, or technology as part of the planning for any future R&D programs. Such centers will be jointly funded by the Federal Government, the private sector, and, where appropriate, the States. They will focus on areas of fundamental research and technology that are both scientifically promising and have the potential to contribute to the Nation's long-term economic competitiveness.

7. Directing the Director of the Office of Science and Technology Policy to convene, within 1 year, an interagency task force of Federal research agencies and their laboratories. The purpose of this task force is to assess the progress in transferring technologies from Federal laboratories. It also develops and disseminates additional creative approaches to technology transfer.

Clearly, Executive Order 12591 represents a strong commitment to improving the cooperation between the Federal Government and industry in areas of research and development. It is perhaps the most comprehensive effort undertaken to foster such cooperation, and will greatly broaden the base of new knowledge available to assure America's continuing competitiveness in the decades to come.

Issue III: Antitrust Law

Background: The antitrust laws were originally intended to protect consumers against abuses of market power, and they have remained largely unchanged for 75 years. Designed to prevent "every contract, combination . . . or conspiracy in restraint of trade," they were often perceived by many in the business community as hindering joint efforts in research and development by effectively prohibiting risk sharing among firms with common interests. It is important that they not be interpreted so as to hinder desirable joint efforts in research and development where no substantial risk of competitive harm exists.

Administration Actions Regarding Issue III

The National Cooperative Research Act of 1984: Enacted by Congress with the support of the Administration, The National Cooperative Research Act of 1984 is intended to ensure that antitrust laws are not a hindrance to joint research efforts. It accomplished this by making modifications in the operation of antitrust laws which changed the incentives for third-party civil suits, thereby reducing the risks associated with engaging in cooperative research. Included among the changes in the law were the following:

1. Clarification that joint research and development is to be analyzed under a "rule of reason" standard that takes full account of its competitive benefits and may not be held unlawful per se.

2. The limitation of what a third party could obtain when filing for recovery. This limitation applies to any of the antitrust acts when filing against persons engaged in joint research and development who have registered under the act. The claimant is limited to damages plus reasonable legal fees, as opposed to the treble damages which had previously been allowed.

3. A provision for the payment from the claimant to the defendant of attorney's fees and other costs of the suit if the claim is judged to be frivolous, unreasonable, without foundation, or in bad faith.

Together, these three provisions of the 1984 act serve to encourage significantly procompetitive collaboration on generic R&D. For many firms, the risks associated with a particular project could be too great to assume alone. Cooperative research and development programs, however, permit firms to share risks, and thereby act as incentive to investment in R&D, in turn making America more competitive in the world market.

In accomplishing this refinement of antitrust statutes, the act strikes a careful balance between maintaining the original intent of antitrust legislation and acknowledging the reality of the contemporary world economy.

The Superconductivity Initiative: The President recommended that the National Cooperative Research Act of 1984 be broadened to cover not only joint research and development but also certain procompetitive joint production ventures. Such conduct would be accomplished under "rule of reason" treatment as well as the act's limitation on damage recourse.

Other Administration Recommendations Regarding Antitrust: The Administration has also recommended a number of other refinements of antitrust law that would help improve further the Nation's competitive position. Included among these would be the following:

1. Amending Section 7 of the Clayton Act to distinguish more clearly between procompetitive mergers and mergers that would create a significant probability of increased prices to consumers.

2. Limiting private and government antitrust actions to actual (rather than treble) damages except for damages caused by overcharges and underpayments.

3. Removing unwarranted and cumbersome restrictions on interlocking directorates.

4. Clarifying the application of U.S. antitrust laws in private cases involving international trade.

5. Requiring that any antitrust claims remaining against other defendants after a partial settlement in a case be appropriately reduced.

Issue IV: Intellectual Property Rights

Background: The maintenance of intellectual property rights such as patents, trademarks, copyrights, and trade secrets is an essential element of any sound R&D plan. U.S. businesses rely upon strong intellectual property protection to realize the benefits of emerging technologies and thereby justify the investment in their development. The rate of development of emerging technologies is directly dependent upon patents as incentives and security for R&D or marketing investment, and upon trademarks to build and protect reputations for quality. Patents permit the ideas or knowledge inherent to inventions to flow into the general pool of scientific information, thus stimulating more innovation. If all inventions were closely held trade secrets, the rate of scientific advances would slow.

Where laws, regulations, or enforcement procedures are inadequate to protect intellectual property rights, the very process of innovation is undermined because its rewards and incentives are eroded. When this occurs, markets are either forfeited, left untapped, or are underdeveloped. The gap left by untapped or undeveloped technology represents a very important social cost of the failure to protect properly intellectual property rights.

Administration Actions Regarding Issue IV

The Competitiveness Initiative: The President, recognizing the importance of intellectual property, proposed in his January 27, 1987, Competitiveness Initiative a four-point program to improve protection of intellectual property rights. The program included the following:

1. A proposal for omnibus intellectual property reform.
2. Measures to protect business confidentiality.
3. The sharing of patent files—that is, making U.S., Japanese, and European patent files available to businesses and universities through private industry or regional search centers.
4. Measures to protect U.S. intellectual property rights abroad by considering patent protection when negotiating international agreements or providing economic assistance.

Executive Order 12591: Under Executive Order 12591, the President has attempted to ensure that there be adequate and effective protection for intellectual property, and encouragement for its development by—

1. Licensing intellectual property developed through the cooperative research and development agreements or by individual Federal laboratories.
2. Implementing royalty-sharing programs for Federal inventors.
3. Developing a uniform Federal policy permitting Federal contractors to retain rights to software, engineering drawings, and other federally generated technical data, in exchange for royalty-free use by, or on behalf of, the Federal Government.

Superconductivity Initiative: The President also included the protection of intellectual property rights in his July 1987 Superconductivity Initiative. The initiative amended U.S. patent laws to increase protection for manufacturing process patents. It also directed the Patent and Trademark Office to accelerate the processing of patent applications and adjudication of disputes involving superconductivity technologies when requested by the applicants to do so.

Patent Appeals Court: Another measure which has helped to improve the protection of intellectual property rights was the creation of a special appeals court to hear patent cases. Prior to its creation, many inventors complained that they could not receive a fair hearing before the Federal appellate bench. The establishment of this new court has had a significant impact on addressing such concerns and has greatly improved the prospects for an inventor to defend successfully a patent.

Issue V: Product Liability and Tort Law Reform

Background: The growing potential for tort law to act as a significant barrier to the introduction of new technologies and the products based upon them arises from a number of factors. Included among them are the following:

1. The gradual erosion of the law of contract as a means of regulating economic activity.
2. The erosion of the concept of informed consent whereby an individual can accept some portion of risk willingly.
3. The move away from the concept of a fault-based liability standard as the basis for economic exchange.

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4. The patchwork of 50 different State liability laws which creates a circumstance wherein cases based on identical facts but tried in different States can have strikingly different and contradictory outcomes.

5. Enormous transaction costs for all parties involved in litigation.

6. The high cost of insurance for product liability-related protection.

Administration Actions Regarding Issue V

The Competitiveness Initiative: In his January 1987 Competitiveness Initiative, the President proposed the following actions to help reduce the barriers created by tort law to the introduction of new technologies and products:

1. Retention of the fault-based liability standard.

2. Elimination of the concept of joint and several liability except where defendants have acted in concert.

3. Limitations on noneconomic damage awards to a fair and reasonable amount.

4. A provision for periodic rather than lump-sum payments of damages for future medical care or loss of income.

5. A reduction of awards in cases where a plaintiff is also compensated by other sources such as government benefits.

6. A reduction in transaction costs through the limitation of an attorney's contingent fees to reasonable amounts on a sliding scale.

7. The encouragement of litigants to resolve their disputes out of court.

Issue VI: Education

Background: One of the most basic requirements for a competitive U.S. advanced materials industry is a properly trained labor force. The requisite numbers of skilled workers, technicians, scientists, and engineers are needed to conduct advanced materials R&D. Of course, other areas of the economy also require similar skills. Education is a key concern for the economy in general and advanced materials in particular.

In 1983, the National Commission on Excellence in Education expressed deep concern over the state of the American educational system. Its 1983 report, "A Nation at Risk," concluded that—

> Our once unchallenged preeminence in commerce, industry, science, and technological innovation is being overtaken by competitors throughout the world. . . . If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war.

Administration Actions Regarding Issue VI

The Competitiveness Initiative: The President's Competitiveness Initiative outlined a number of goals aimed at regaining America's preeminence in education. These include the following:

1. Improving basic skills: The Administration has produced a number of studies and reports on education reform and excellence to provide useful guidance to local school systems trying to improve basic skills. It is also working with State Governors to identify places of excellence that can serve as models.

2. Raising standards: The Administration has encouraged raising standards for our high school graduates to include significantly higher requirements for English, science, mathematics, and computer proficiency.

3. Helping Needy Schools and Youth: The Administration has proposed reauthorization of Chapters 1 and 2 of the Education Consolidation and Improvement Act to target resources to the neediest schools and students.

4. Establishing a goal of dramatically reducing illiteracy by the end of the century.

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5. Submitting proposals to reform bilingual education.

6. Increasing scientific literacy: The President is directing the National Science Foundation and all other Federal agencies to work with the Departments of Education and State and local governments to assure that our children have the scientific literacy needed for the 21st century.

To promote interest in careers in science and engineering, these agencies will—

1. Establish internships for promising students at federally supported research labs.

2. Advise in the development of first-rate scientific and technical curriculums for all educational levels using the expertise of top U.S. scientists and engineers.

3. Provide matching contributions to primary and secondary schools and universities for instructional scientific equipment and computers.

4. Undertake promotional efforts regarding science and technology careers for minorities and women.

Department of Defense Industrial Base Initiative: In addition, through the Department of Defense "Industrial Base Initiative," the Administration has made a number of other proposals to help improve the education of scientists and engineers. One of the most important is a proposed scholarship program to be offered to schools that have the following:

1. A strong commitment to maintaining the leading edge in expertise in industrial technologies.

2. Industrially supported faculty positions to enable the world's best manufacturing managers to teach future generations.

3. Industrial hiring programs to ensure that the finest career opportunities are afforded the new generation of manufacturing managers.

4. State and university commitments for faculty and curriculum development to ensure that the United States remains on the leading edge of the development of management and technological progress.

The Department of Defense has also proposed taking on the leadership of a national program to stimulate both undergraduate and graduate technical programs to assure both the quantity and quality of technically qualified graduates for the Nation's needs.

Issue VII: Government's Role In Research Funding

Background: U.S. manufacturers in many cases are unable to get products from research and development to the market as fast as is necessary to be competitive. Many experts believe that part of the cause of this problem has been an inadequate investment in process and manufacturing research. While such research must primarily be the responsibility of the private sector, the Administration has proposed a number of programs which would help to address this problem.

Administration Actions Regarding Issue VII

The Competitiveness Initiative: The Administration's competitiveness initiative included several elements aimed at promoting greater research into process and manufacturing technologies. Among these were the following:

1. Establishment of Science and Technology Centers, including centers concerned with automated manufacturing and new methods of materials processing.

2. Creation of an incentive for private sector research and development through the provision of research and development tax credit.

3. Research into improved manufacturing technology.

Department of Defense Industrial Base Initiative: In addition, the Department of Defense, through its Industrial Base Initiative, has also proposed

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a number of actions to help encourage research into process and manufacturing technologies. Included among them are the following:

1. Development of manufacturing technology as part of all basic science programs.

2. Development of manufacturing technology in all weapon systems development programs.

3. Greatly expanded emphasis on and resources for the Manufacturing Technology Program.

Indirect Research Policy—Tax Policy: Tax policy has long played a major role in domestic business decisions. A major goal of the Administration has been to eliminate those elements of the tax code which distorted markets or which unduly subsidized or penalized selected sectors or individuals within the economy. The single most important incentive proposed by this Administration is to keep the Nation's tax burden as low as possible consistent with prudent financial practices.

The Competitiveness Initiative: Under the Competitiveness Initiative, the Administration has sought two specific provisions to ensure the financial incentives for private research and development. The Administration sought legal and regulatory stability for the research and development tax credit and Section 861 rulings on the allocation of R&D expenditures overseas.

Issue VIII: Regulatory Policies

Background: A major potential barrier to the introduction of new technologies and products lies in the so-called "command and control" design regulations that mandate certain technologies by law. However, this approach can be overly rigid and can stand in the way of the introduction of new technologies.

The use of the command and control design also presents a problem in winning clearance for new technologies which could be more effective and less costly. This can be particularly onerous for the introduction of new manufacturing or production technologies for which there are no existing regulations in place. Attempts to apply standards developed for existing technologies to newly emerging ones can often result, for example, in the imposition of unneeded pollution-abatement equipment at great cost, or conversely, the failure to properly require controls for emissions which had not previously been regulated.

At the same time, the development of new standards and regulations can be time consuming and expensive, leading to delays that permit foreign competitors who do not have to meet stringent requirements to gain a competitive advantage. A far better approach, therefore, lies in performance-based standards that do not mandate specific technologies, but instead concern themselves with actual results.

Administration Actions Regarding Issue VIII

The Competitiveness Initiative: In his 1982 National Materials and Minerals Program Plan, the President made the reform of excessively burdensome regulations a major priority. This commitment was reaffirmed in his January 1987 Competitiveness Initiative where he charged the Vice President's Task Force on Regulatory Relief with the responsibility of taking a fresh look at the Federal regulatory structure from the competitiveness standpoint, improving the cost effectiveness of regulations, and eliminating unnecessary regulatory burdens.

Issue IX: International Research and Development Issues

Background: With the advent of a global marketplace, research, too, has become transnational in nature. As a result, innovations developed beyond our borders can be of vital importance to our continuing competitiveness. One way to assure access to the technologies developed abroad is by being an active participant in their development. For this to happen, U.S. scientists, engineers, and businessmen must involve themselves in projects abroad. The Administration has worked diligently to help provide opportunities for such involvement.

Administration Actions Regarding Issue IX

The U.S.-Japan Science and Technology Agreement: One of the most far-reaching actions of the Administration to further domestic

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research and development was the successful conclusion of a precedent-setting U.S.-Japan Science and Technology Agreement. Signed by the President on June 20, 1988, in Toronto, Canada, the agreement provides a framework for broad cooperation and incorporates the key tenets of the Administration's science and technology policy. Included among the provisions of the pact are these:

1. Provisions setting forth the broad principles under which the Governments of the United States and Japan will conduct their future science and technology relationship.

2. Provisions establishing cooperation in science and technology areas of national importance in which both countries have complementary capabilities and from which both countries will obtain equitable benefits (superconductivity is among these areas of research).

3. A call for both Governments to provide comparable access to major government-sponsored or supported research facilities and activities as well as to scientific and technical literature.

4. Creation of a broad management structure that will oversee the overall science and technology relationship and generate new initiatives for the two Governments to implement and strengthen the relationship.

5. Delineation of provisions for the adequate protection of intellectual property and the distribution of intellectual property rights arising from the collaborative activities under the agreement.

6. Details of the shared security obligations of the United States and Japan in the area of science and technology information and equipment as well as a statement that both countries will support the widest possible dissemination of information subject to export control classification procedures.

Export Controls: The U.S.-Japan Science and Technology Agreement points out the importance of export control classification procedures to doing business and sharing information internationally. While the need for control of the export of technology for purposes of U.S. national security has been clearly established, questions have been raised about whether there has been "overcontrol."

The President's January 1987 Competitiveness Initiative directed the Cabinet to review the export controls program and provide recommendations to achieve the following:

1. Decontrolling those technologies that offer no serious threat to U.S. security.

2. Strengthening enforcement controls on those technologies that could harm U.S. security.

3. Eliminating unilateral controls in those areas where there is widespread foreign availability.

4. Reducing the time required to acquire a license by at least one-third and implementing a fair, equitable, and timely dispute-resolution process.

5. Seeking agreement with our allies for concrete actions that will make export control procedures more uniform and enforcement more rigorous.

6. Seeking to level the overall competitive playing field while strengthening multinational controls over products and technologies that can contribute to Soviet military capabilities.

SUMMARY

Coordination and communication within the Federal Government and between the public and private sectors regarding science and technology have been a major target of Administration actions. Approaches include the upgrading of COMAT included in the 1982 National Materials and Minerals Program Plan and enhanced coordination in the Superconductivity Initiative and Executive Order 12591.

An additional area of concern is the impact of antitrust, tort law, and the protection of

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intellectual property rights on the development of advanced materials. Components of the Competitiveness Initiative, the Superconductivity Initiative and the Cooperative Research and Development Act deal with these areas of concern.

Issues concerning the enhancement of education, government support for generic research, and regulatory policies in general are also addressed in the Competitive, Superconductivity, and Industrial Base Initiatives, as well as the 1982 Program Plan. International cooperation is addressed in the above initiatives and plans as well as in the U.S.-Japan Science and Technology Agreement. The policy framework presented in matrix form as Figure 5-1 is the third key component of the Program Plan.

Figure 5-1. Advanced Materials Program Plan Policy Framework

	Government Actions					
Issues	**Competitive Initiative**	**Superconductivity Initiative**	**Industrial Base Initiative**	**1982 Plan**	**Cooperative R&D Act**	**U.S.-Japan Science & Technology Agreement**
Coordination & Communication Within Government		X		X		
Coord. & Comm. Government/ Industry/ Academia	X	X	X	X	X	X
Antitrust Laws	X	X			X	
Intellectual Property Rights	X	X			X	
Product Liability Tort Law	X					
Education	X	X	X	X		
Government Research Policy	X		X			
Regulatory Policies	X			X		
International Cooperation	X			X		X

X = contains a component to address this issue area

PART VI

SUMMARY AND CONCLUSIONS

The three key components of the Advanced Materials Program Plan are the technical constraints (general and materials-specific) that must be overcome so these materials can fully achieve their technological potentials; Federal materials program descriptions; and a policy framework for advanced materials research and development. Followup is needed to ensure that the actions initiated by the current Administration to address the issues identified in the policy framework bring about their intended results.

The three key components of the Advanced Materials Program Plan are summarized below. These components are the technical constraints (general and materials-specific) that must be overcome so these materials can fully achieve their technological potentials; Federal materials program descriptions; and a policy framework for advanced materials research and development. These components, when combined, give the current status of advanced materials developments in the United States, as well as summarizing important related policies for the approach to coordination of Federal research and development (R&D) activities and the exchange of information with private sector efforts.

GENERAL TECHNICAL CONSTRAINTS

Phase one of the plan was to identify specific technical areas which act as constraints to advanced materials development. Some of the more important are the following:

1. Better understanding of structure-property relationships.
2. Improved physical property data bases.
3. Approved test methods for new materials, especially nondestructive evaluation methods.
4. Methods to assess deterioration in use so that product life-cycle costs can be estimated.
5. Improvements in joining technologies of dissimilar materials.

MATERIALS-SPECIFIC TECHNICAL CONSTRAINTS

In addition to general technical constraints that apply to many material types, there are technical constraints that are specific to each materials category. Some of the more important are as follows:

1. **Metals and Alloys:** Better understanding of metastable states regarding rapidly solidified alloys; improvements in forming mechanisms for powder metallurgy, especially in regard to net shape forming methods; and better understanding of coatings.
2. **Structural Ceramics:** Control of critical flaws that lead to brittleness and solving fabrication problems in forming ceramics to close dimensional tolerances.
3. **Engineering Polymers:** Better methods for controlling surface finishes and new surface coatings, as well as better fillers and colorants; designing components for easy repair; and addressing the problem of solid waste disposal (recyclability).
4. **Advanced Composites:** Understanding the forces operating between the matrix and the reinforcing materials; requirement for uniform, predictable, and controllable distribution of the reinforcing phase; and improvement on labor-intensive fabrication methods and curing methods.
5. **Electronic, Magnetic, and Optical:** Trends toward further miniaturization, combination of electronic and optical circuits, and a new generation of sensors and

emitters; need to remove heat from circuitry leads to research into materials with high thermal conductivity, such as aluminum nitride and diamond films.

6. **Medical and Dental Materials:** Evaluation of long-term durability is the high priority.

RESEARCH AND DEVELOPMENT PRIORITIES

The U.S. Federal Government now spends slightly more than $1 billion per year on materials research. The funds are largely concentrated in six agencies and are spent in pursuit of statutorily required agency missions. The Department of Energy spends about $480 million. The Department of Defense spends another $181 million. The National Aeronautics and Space Administration materials budget is about $157 million. The National Science Foundation budget is $137 million; NSF distributes funds to researchers in academic institutions and elsewhere. The remaining funds are allocated through the Bureau of Mines and the National Institute of Standards and Technology; each receives about $24 million.

Programs are carried out to meet the goals and objectives of the implementing agencies. At the same time, interagency coordination of R&D activities are carried out through the mechanisms discussed in Part V.

POLICY FRAMEWORK

There are nine policy areas crucial to the development of advanced materials. Those areas, as described above, are as follows:

1. Coordination and communication within Government.
2. Coordination and communication among Government, industry, and academia, including but not limited to technology transfer.
3. Antitrust constraints (perceived and actual) on joint R&D ventures.
4. Intellectual property rights.
5. Product liability and tort law.
6. Education.
7. The Federal Government's role in R&D funding, including tax incentives.
8. General regulatory policies.
9. International issues regarding R&D, including cooperation and export control policy.

The linking of these issues to the Federal Government's actions provides an important component of the Program Plan. Through the 1982 National Materials and Minerals Program Plan, the Cooperative R&D Act of 1984, the Competitiveness Initiative (1987), the Superconductivity Initiative (1987), the Industrial Base Initiative (1987) and the U.S.-Japan Science and Technology Agreement of 1988, the Administration has worked with Congress to put forward the policy framework for an advanced materials Program Plan that is both realistic and sensible.

FOLLOWUP ACTIONS

This plan presents the current status of advanced materials research and development. Followup is needed to ensure that the actions initiated by the current Administration bring about their intended results. Efforts are needed to continue to improve coordination of advanced materials R&D among the involved agencies, as well as the National Critical Materials Council, the Office of Management and Budget, and the Office of Science and Technology Policy. The issues identified here must continue to be reviewed so that the existing mechanisms can be improved and new actions taken where needed.

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APPENDIX

CLASSIFICATION OF ADVANCED MATERIALS

I. Metals

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
A. Structural				
Superalloys	Co-based, Ni-based, with Cr, Mo, Cb, Ta, W, Hf, Zr	Investment cast as polycrystalline, directionally solidified, or single crystal	High strength at high temperatures; corrosion resistance	Jet engine components resistance wire
Aluminum-Lithium Alloys	Al-Cu and Al-Mg with 1-3% Li	Conventional	Low density; high stiffness	Aircraft skin and structure
Amorphous Alloys	Fe-based, Co-based, with Al	Rapidly cooled	High hardness and tensile strength; corrosion resistance; high magnetic permeability, free of anisotropy; high electrical resistance	Reinforcement for composites; corrosion resistance materials; magnetic applications
Rapidly Solidified Alloys	Al-Si; many alloy systems	Very rapidly cooled as powders, ribbons	Solid solubility increased; all properties altered	High-strength powder metallurgy products
Superfine Particles	Many alloy systems	Liquid metal atomized to form submicron particles	Large surface areas; paramagnetic; high reactivity; high sinterability	Catalyst carriers; filters; sintering aids; fillers
Ordered Intermetallics	Ni Al; Cu-Al-X alloys (X=Fe, Ni, Mn, Be, Co, Si, Sn)	Conventional, with annealing to obtain correct phase content and microstructure	Resistance to corrosion and corrosion fatigue; high strength in heat-treated forms	Structural materials with hot corrosion resistance; jet engine components; ship construction
Shape Memory Alloys	Cu-Zn-X (X=Si, Sn, Al, Ga); Cu-Zn; Cu-Al-Ni; Cu-Sn; Cu-Au-Zn; Ni-Al; Ti-Ni; others	Conventional, shaped below transition temperature	Regains original shape when heated above transition temperature	Pipe clamps, sensors, and actuators; orthodontic wire; eyeglass frames; specialty rivets; kinetic energy storage
Copper-Beryllium Alloys	Cu-Be	Conventional	High strength increases with temperature; high fatigue resistance; high thermal conductivity	Precision current-carrying springs; electrical connections test probes; components for robots

I. Metals—*continued*

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
Surface-Hardened and Coated Metals	Carbides, nitrides, and borides of B, Cr, Hf, Mo, Cb, Si, Ta, Ti, V, W, Zr; zirconia and mullite coatings	CVD; PVD; thermal spray; plasma spray	Corrosion, wear, and heat resistance	Many structural applications
Titanium Alloys	6% Al, 4% V, etc.	Conventional	Low density, high strength at medium temperatures, toughness, corrosion resistant	Airframes, skin, turbine parts
Superplastic Alloys	Ti alloys; superalloys	Fine grains for superplasticity, followed by heat treatment for strength	Fewer machining and finishing steps	Aircraft structure and engine components
B. Absorptive				
Hydrogen Storage Alloys	Li, Mg, Y, V, Cb, Pd, U, FeTi, $LaNi_5$	Conventional	Retain more H_2 than tanks at moderate pressure; absorption and release reversible with temperature change	Stationary or mobile storage; heat engines; water splitting; H-isotope separation; fusion reactor technology
Porosity Metals	Alloys of Ni, Cr, Cu, Al, Ag, Zn, Pb	Foamed during solidification	Up to 98% pore volume; continuous pores	Electrode plates; catalyst carriers; filters
C. Composites				
	Matrices of Al, Cu, Zn, Ti, Ni; reinforcements of Al_2O_3, mullite, B, and SiC fibers; SiC whiskers; Al_2O_3, SiC, Si_3N_4 particulates	Prepreg lay-up for continuous fibers; casting or CVD of matrix	High strength and fracture toughness; low densities	Aircraft, automotive, and ship structural components; machinery; space structures

II. Structural Ceramics

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
D. Monolithic				
Oxides	Al_2O_3; partially stabilized ZrO_2 (PSZ); tetragonal zirconia polycrystal (TZP); BeO; cordierite; SiO; mullite; Al_2TiO_5; Y_2O_3; ThO_2	Prepared as submicron powders; formed by pressing; sintered at high temperatures with or without pressure	Heat resistance; strength; wear resistance; corrosion resistance	Turbine blades; adiabatic engine components; heat exchangers; cutting tools; bearings; catalyst carriers; mechanical seals; nozzles; RF crucibles; nuclear shielding
Non-oxides	SiC, Si_3N_4, SIALONS, B_4C, AlN, hexagonal BN, cubic BN, TiB_2, ZrB_2, TiN, TiC	Prepared as submicron powders; formed by cold or hot pressing, with or without sintering aids; sintered at high temperatures, with or without pressure	Heat resistance; oxidation resistance; strength at high temperatures; greater toughness	Same as above, except for catalyst carriers
E. Composites				
	Matrices of oxides and non-oxides; reinforcements of C, SiC, Si_3N_4, Al_2O_3, and aluminosilicate fibers; SiC whiskers; PSZ particulates	Processing not yet developed; fiber prepregs treated with slurry	Heat resistance; improved fracture toughness; "graceful" fracture	All the applications of monolithic ceramics
	Carbon matrix/carbon fiber composites	Continuous fiber prepregs; CVD carbon matrix	Heat resistance; strength; low density; (needs protection from oxidation)	National Aerospace Plane skin; rockets and missiles; space structures

III. Engineering Polymers

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
F. Structural	Polybutylene terephthalate (PBT); polyethylene terephthalate (PET); poly (4,4' isopropylidine diphenylene carbonate) (polycarbonate); polyether sulfone; polyarylate; polyphenylene sulfide (PPS); polyamide-imide; polyetherether ketone (PEEK); poly (paraphenylene benzobisimidazole) (PBI); poly (paraphenylene benzobisoxazole) (PBO); poly (paraphenylene benzobisthiazole) (PBT); liquid crystal polymers; polymer blends	Chemical reactions of resins with reagents at elevated temperatures; blow molded; injection molded; sheets; films; pultruded	Melting temperatures between 240 °C and 530 °C; high strength and stiffness; low densities	Structural materials for aircraft, automobiles, office equipment; electromagnetic interference shieldings
G. Composites	Matrices of any of the thermoset resins or thermoplastics; reinforcement of glass fibers, boron fibers, carbon fibers, chopped fibers, whiskers	Continuous fiber prepregs laid before pouring or molding; chopped fibers, whiskers, and particulates added prior to reactions	Very high tensile strengths and fracture toughness; low densities	Structural materials for multitude of applications

IV. Functional Devices

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
H. Electronic and Optical				
Dielectrics	Al_2O_3, BeO, AIN, diamond film, MgO, polyimide	Ceramic sintering, CVD, polymer reaction	Electrical insulation; thermal conductivity	IC substrates, packaging
Ferroelectrics	$BaTiO_3$, $SrTiO_3$	Ceramic sintering	Dielectric over defined voltage range	Ceramic capacitors
Piezoelectrics and Nonlinear Optical Devices	Quartz, lead zirconium titanate (PZT), lead lanthanum zirconium titanate (PLZT), $LiNbO_3$, ZnO, polydiacetylene (PDA), liquid crystals	Ceramic sintering, CVD, polymer monolayers, single crystal growth	Piezoelectric or nonlinear optical properties	Vibrators, oscillators, transducers, spark generators, optical switches, optical modulators
Semiconductors	Si, GaAs, SiC, In GaAsP/InP, GaAlAs/GaAs, HgCdTe, Cd (S, Se), ZnO-Bi_2O_3, V_2O_5, In-Cu-Se/Zn-Cd-S	Single crystal growth, CVD, molecular beam epitaxy	Semiconducting over defined and controllable ranges; optical transparency for some uses	Integrated circuits, solar cells, thermistors, sensors, varistors
Light Emitters	GaAs, Gap, PLZT, yttrium aluminum garnet (YAG), InP	Single crystal growth, CVD; ceramic sintering	Electricity-light conversion	Laser diodes, light-emitting diodes, phosphors
Optical Fibers and Transparent Ceramics	SiO_2, Al_2O_3, AlON, MgO, Y_2O_3-ThO_2, Ba-La-Zr-Al-Na-F, polymethylmethacrylate, selenide glasses	Glass fiber pulling and chemical treatment	Optical transparency with low loss over a range of wavelengths	Fiber communications, IR transmitters, high-pressure lamps
Ionic Conductors	Beta-Al_2O_3, ZrO_2, ZnO, Fe_2O_3, SnO $MgCR_2O_4$-TiO_2	Ceramic sintering	Ion-specific conductivity	Solid electrolytes, fuel cells, humidity sensors, oxygen sensors, hydrocarbon and fluorocarbon detectors

IV. Functional Devices—*continued*

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
Superconductors	Ni-Ti, V_3Ga, Nb-Ti, Nb-Sn, $YBa_2Cu_3O_x$-type ceramics	Metal-forming ceramic sintering, CVD thin films	Zero resistance, magnetic field strength, current density, Josephson effect, Meissner effect	High speed LSI, electromagnets for NMR imaging, magnetic levitation, power transmission, transformer cores
I. Magnetic				
Metallic	SrCo, powder alloys, Nd-Fe-B, superconductors	Metal forming	Magnetic field, permanent or electromagnetic	Magnetic heads and tapes, transformer cores, motors, NMR imaging instruments
Ceramic	$BaFe_{12}O_{19}$, $SrFe_{12}O_{19}$, $YBa_2Cu_3O_x$-type ceramics, other ferrites	Ceramic powders, ceramic sintering, CVD	Magnetic field, reversible polarity	Magnetic tapes, motors, NMR

V. Medical and Dental

Materials Class	Chemistry and Form	Processing Methods	Critical Properties	Uses or Potential Uses
J. Structural				
	Al_2O_3 structures	Fine powders sintered at high temperatures	Biologically inert; corrosion resistant; high strength	Bone replacements
	Hydroxyapatite	Formed as a glass; cast	Biologically compatible	Bone and teeth replacements
	Carbon fiber/polylactic acid composites	Chemical formation of PLA on C fiber prepreg	Histocompatibility; dissolves as healing occurs	Tendon replacements
K. Functional				
	Silicone, fluoropolymers	Chemical reaction; polymer forming	Histocompatibility	Artificial blood vessels; heart repair; soft tissues
	Acrylic, methacrylic resins	Chemical reaction; polymer forming	Histocompatibility	Artificial kidneys

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DATE FILMED

07/28/95